AN EVALUATION OF THE HAZARD PREDICTION AND ASSESSMENT CAPABILITY (HPAC) SOFTWARE'S ABILITY TO MODEL THE CHORNOBYL ACCIDENT

THESIS

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AFIT/GNE/ENP/02M-06

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THESIS

Presented to the Faculty

Department of Engineering Physics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for

Degree of Master of Science (Nuclear Engineering)

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March 2002

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Acknowledgements

I would like to thank my advisor, Lieutenant Colonel Vince Jodoin, without whose motivation, patience and constructive criticism I would not have completed my research. I'd also like to thank the members of my committee, Dr. Glen Perram and Dr. Dennis Quinn, for their insight, suggestions and feedback.

Although too many to mention, several individuals provided insight and assistance during my research. They include personnel at AFIT, Air Force Combat Climatology Center, Defense Threat Reduction Agency Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, and the Commission of the European Communities Joint Research Center.

I wish to thank my classmates in the nuclear engineering program for their daily, unspoken inspiration. Knowing that others were going through the same difficulties made the effort bearable and worthwhile. It has been a pleasure and a learning experience working beside them.

Dirk E. Plante

> "No profession or occupation is more pleasing than the military; a profession or exercise both noble in execution (for the strongest, most generous and proudest of all virtues is true valour) and noble in its cause. No utility either more just or universal than the protection of the repose or defence of the greatness of one's country. The company and daily conversation of so many noble, young and active men cannot but be well-pleasing to you."
>
> Michel de Montaigne (1533-92),
> French essayist.

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Abstract

The performance of the Nuclear Facility (NFAC) incident module in modeling a nuclear reactor accident is evaluated. Fallout predictions are compared with air concentration measurements of I-131 in Europe over a five-day period. Two categories of source term specifications are used: NFAC-generated source terms based on plant conditions and accident severity, and user-defined source terms based on specifying the release of I-131. The Atmospheric Transport Model Evaluation Study report source term provided the needed detailed release information. The Air Force Combat Climatology Center provided weather data covering Europe during the release's 11-day duration.

For the NFAC-generated source terms as few as 20% and as many as 52% of the values are within the intended accuracy, depending on which source term specification was selected. For the user-defined source terms, values ranged 35% to 56% being within the intended accuracy, again depending on which source term specification was used. Performance improved in all cases for monitoring sites closest to Chornobyl, with up to 87% of the values falling within the intended accuracy. This indicates there may be a limit for selecting the spatial domain, making HPAC more useful as a tool for smaller spatial domains, rather than on a continental scale.

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I. Introduction

Motivation

The terrorist attacks on the United States in September 2001 resulted in a heightened state of concern regarding the safety of the nation's 103 nuclear power plants, and the potential for attacks. These facilities are a viable terrorist target that could result in a significant release of radioactive material. Although design and operational features make the probability of an accidental release of radioactivity very low, when they were constructed U.S. nuclear plants were not required by 10 CFR Part 100 to withstand the crash of an aircraft [Nuclear News, 2001:14]. Furthermore, accidents or attacks on reactors in other nations are important to the U.S. since radioactive material can be dispersed globally. Therefore, a requirement exists for a software tool to predict the consequences of a significant release of radioactivity from a nuclear power plant.

The Defense Threat Reduction Agency (DTRA), with the stated mission to safeguard "America and its friends from weapons of mass destruction" (WMD), has developed the Hazard Prediction and Assessment Capability (HPAC) software for evaluating the consequences for many nuclear, biological and chemical (NBC) scenarios. Although users of the software are most interested in predicting the consequences of scenarios yet to happen, it is important to study previous events using detailed inputs in

order to determine the degree to which the software is able to accurately predict consequences formerly measured.

Background

The HPAC software is a counterproliferation and counterforce tool that predicts the effects of NBC material releases into the atmosphere and its collateral effects on civilian and military populations. The software contains six incident models (also called source term models) that estimate the releases from different threat scenarios. These models fall into two categories: WMD Usage and NBC Releases. Table 1 provides a description of the six models. The Nuclear Facility (NFAC) incident model is the focus of this research. Updates of the software will incorporate other incident models, including the Nuclear Weapon Incident (NWI) model for modeling "broken arrow" scenarios (loss of control or theft of a nuclear weapon).

Table 1. Description of the HPAC Source Term Models

Incident Model	HPAC Category	Description
Chemical Biological Weapon (CBWPN)	WMD Usage	Release of material from chemical and biological weapons
Nuclear Weapon (NWPN)	WMD Usage	Release of radioactive material from detonation of a nuclear weapon
Radiological Weapon (RWPN)	WMD Usage	Release of radioactive material by explosion dispersion (non-nuclear)
Chemical/Biological Facility (BFAC/CFAC)	NBC Release	Conventional warhead attack on chemical and biological facilities
Nuclear Weapon at Biological Facility (NWBFAC)	NBC Release	Nuclear weapon detonation at a biological facility
Nuclear Facility (NFAC)	NBC Release	Accidental release of radioactive material to the atmosphere

The HPAC software performs its function in three sequential steps: hazard source definition, transport, and effects. Hazard source definition requires the use of one of the incident models to define the what, where and when of an incident. For the NFAC model this involves identifying the nuclear facility, the type of accident at the facility and the specifics of the release. An alternative to defining the release in NFAC is to prepare a Rad file outside of NFAC to allow for greater control over the source term specification. (The origin of the name 'Rad file' is unknown [Sjoreen, 2002]. It is the three-letter suffix used for the file calculated by the source term generator in the HPAC software.) The source term algorithm in the HPAC software is based on a methodology prepared by the Nuclear Regulatory Commission (NRC). This methodology states that even if all the accident conditions are known, the best one can hope for in estimating the true source term is within a factor of 100 [NUREG-1228, Ch. 1:8]. Source term specification will be discussed further in Chapter III and Appendix A. Transport involves the use of a transport and dispersion model to accurately move the NBC material through the atmosphere, and calculate deposition at geographic locations. The transport model used in HPAC is the Second-order Closure Integrated Puff (SCIPUFF) model, a Lagrangian frame of reference, Gaussian puff model. As with source term definition there is a limit to the accuracy of a transport model. Even a complex model such as SCIPUFF will be limited to about a factor of two [Eisenbud:81]. Weather and terrain data, defined by the user in the incident model during the hazard source definition step, and other files created by NFAC are used by SCIPUFF to accurately transport the hazard. Effects, the final step of the sequence, provides the user with a map interface that displays the consequences of

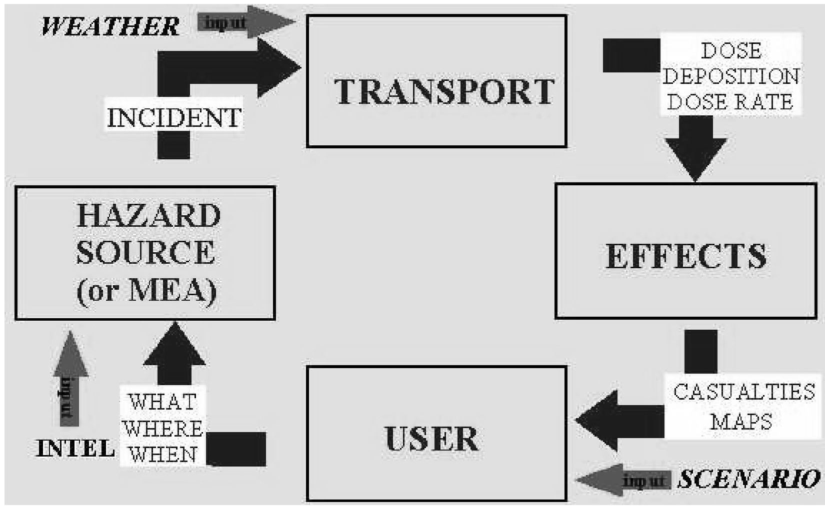

Figure 1. HPAC Sequence [DTRA, 2000:Ch. 10]

the release on the surrounding area. Calculated results include air concentration, ground concentration, horizontal slice, radiation dose and radiation dose rate, that are available to plot. Figure 1 illustrates the HPAC sequence.

Modeling the Chornobyl accident serves a useful purpose: A recent query on the International Atomic Energy Agency's website (www.iaea.org/worldatom/) of operational reactors indicated that 17 RBMK (Russian acronym for *Reactor Bolshoi Moschnosti Kanalynyi*, meaning *Channelized Large Power Reactor*) reactors are still in use in Russia and Lithuania. A previous thesis studied NFAC using the Three Mile Island accident, a scenario with a lesser release and local fallout footprint [Frederick, 2000].

Problem Statement

The research objective is to evaluate the performance of the NFAC module of the HPAC software using the Chornobyl accident as a single case study and determine the software's usefulness for modeling nuclear facility accidents.

Scope

This research focuses on the NFAC module of the HPAC version 3.2.1 software to model the accident at the Chornobyl Nuclear Power Plant (NPP). Modeling the Chornobyl accident should challenge the HPAC software due to the sheer magnitude of the disaster, the particulate nature of the release, and the extent of the fallout. During this research project, DTRA released a new version of HPAC (4.0). However, the modifications made to the NFAC module produced incorrect results [Sjoreen, 2001b]. Oak Ridge National Laboratory (ORNL) made available a beta of HPAC version 4.0.1 that corrected the problems in NFAC. However it did not integrate all the features of version 3.2.1. Although the SCIPUFF transport and dispersion model is a vital part of the HPAC software, its performance is not evaluated in this research. The transport and dispersion model has been verified and validated in the development process of the HPAC software [Bradley, *et al.*].

General Approach

The research began with a literature review of the Chornobyl accident to understand the cause of the accident and the source term. Several publications provided a thorough accounting of the accident, including “Chernobyl Record” [Mould], and the NRC technical report “Report on the Accident at the Chernobyl Nuclear Power Station” [NUREG-1250]. The most comprehensive study of transport models to predict the fallout from the accident is documented in the 1992 study, “Evaluation of Long Range Atmospheric Transport Models using Environmental Radioactivity Data from the Chernobyl Accident: The ATMES Report” [Klug, *et al.*]. The Atmospheric Transport

Model Evaluation Study (ATMES) report used data collected from iodine-131 (I-131) and cesium-137 (Cs-137) concentrations measured throughout Europe. Twenty-one transport models from organizations worldwide were evaluated in the study.

The HPAC software was run using different source term specifications, including an external Rad file that modeled the ATMES source term. Appendix A provides information on the custom Rad file created to model the I-131 releases. Input parameters were varied in order to attempt to model the resulting fallout from the Chornobyl accident. Point-wise comparisons for specific geographic locations were made with the dataset of I-131 air concentrations and the predictions obtained from the HPAC software runs.

The Air Force Combat Climatology Center (AFCCC) in Asheville, North Carolina provided the external weather data used in the research. The information consisted of soundings (i.e. weather data) during the accident time period from 119 upper-air profile stations and several hundred surface observation stations in Europe. The upper-air profile had a resolution of observations every six hours, and the surface observations provided data several times each hour. Software simulations using both upper-air and surface data were conducted. Appendix B provides additional information on the weather data and its format.

Thesis Overview

This document consists of five chapters and three appendices. Chapter II presents an account of the Chornobyl accident, including background information on the reactor design and how it contributed to the cause of the accident. A description of the NFAC incident model and its methodology are presented in Chapter III, providing information

on the several ways an analyst can model the Chornobyl accident. Chapter IV presents the results of the HPAC data runs, and contains the HPAC predictions and comparison to actual measured data from the accident. All of the results are presented in tabular form, with some of the results also presented as the contour plots produced by the software. Chapter V includes the research summary, conclusions, recommendations for modifying the HPAC software, and recommendations for future research. A glossary of acronyms and other technical terms is included on page 91. Three appendices provide information on preparation of the custom Rad file, a description of the weather data formats, and additional HPAC contour plots not provided in the results chapter.

Use of Place Names and Times

In 1986 the Soviet Union was comprised of 15 constituent republics, including the Ukraine Republic. At the time of the accident the accepted spelling of the power plant and the city was the Russian spelling of “Chernobyl.” Today, Ukraine has sought to re-institute its spelling of “Chornobyl.” This is now the accepted spelling by the Board on Geographic Names (BGN) of the United States Geological Survey (USGS). In this thesis the current version is specified except when used in the titles of books, tables and figures published with the old spelling.

Ukraine is located in Eastern Europe. Results of the literature review found the local time at Chornobyl to be GMT+2 (Greenwich Mean Time plus 2 hours), GMT+3 and GMT+4 (GMT is also known as Universal Time Coordinated, UTC, or Zulu time). Many documents provided only the local time for activities at Chornobyl. The database in HPAC recognizes the time at Chornobyl as GMT+2, as does the website www.timezone.org. However, review of documents published soon after the accident

gave the time as GMT+4. The GMT+4 time is used to standardize the use of times in the figures, tables, and HPAC software data runs.

II. The Chornobyl Accident

This chapter provides design information for the Chornobyl reactor and an account of the accident. It also includes a comparison with the accident at Three Mile Island to provide a perspective of the severity of both accidents.

Chornobyl Nuclear Power Plant

The unit #4 reactor was one of four identical reactors operating at the Chornobyl NPP (officially named the V.I. Lenin NPP) in the Ukraine at the time of the accident. Construction of unit #4 was completed in December 1983 and it went on line in April 1984. Two additional units were under construction at the power plant at the time of the accident, with completion scheduled for 1985 and 1986. The Soviet Union showed considerable pride in the RBMK design, and considered it "to be their 'national' reactor" [NUREG-1250, Chap 2:3]. Figure 2 provides a cutaway view of the unit #4 reactor facility.

The RBMK Design

The RBMK design is graphite-moderated and light water-cooled, using uranium fuel that is slightly enriched (2% uranium 235) uranium dioxide (UO_2). It is a uniquely Soviet design that is no longer used anywhere else in the world. At the time of the accident there were 20 reactors of the RBMK design operating in the Soviet Union [Morris, 1996:4]. The RBMK design was chosen in the 1960s as the Soviet's first type of reactor for power generation because they had significant experience in running graphite

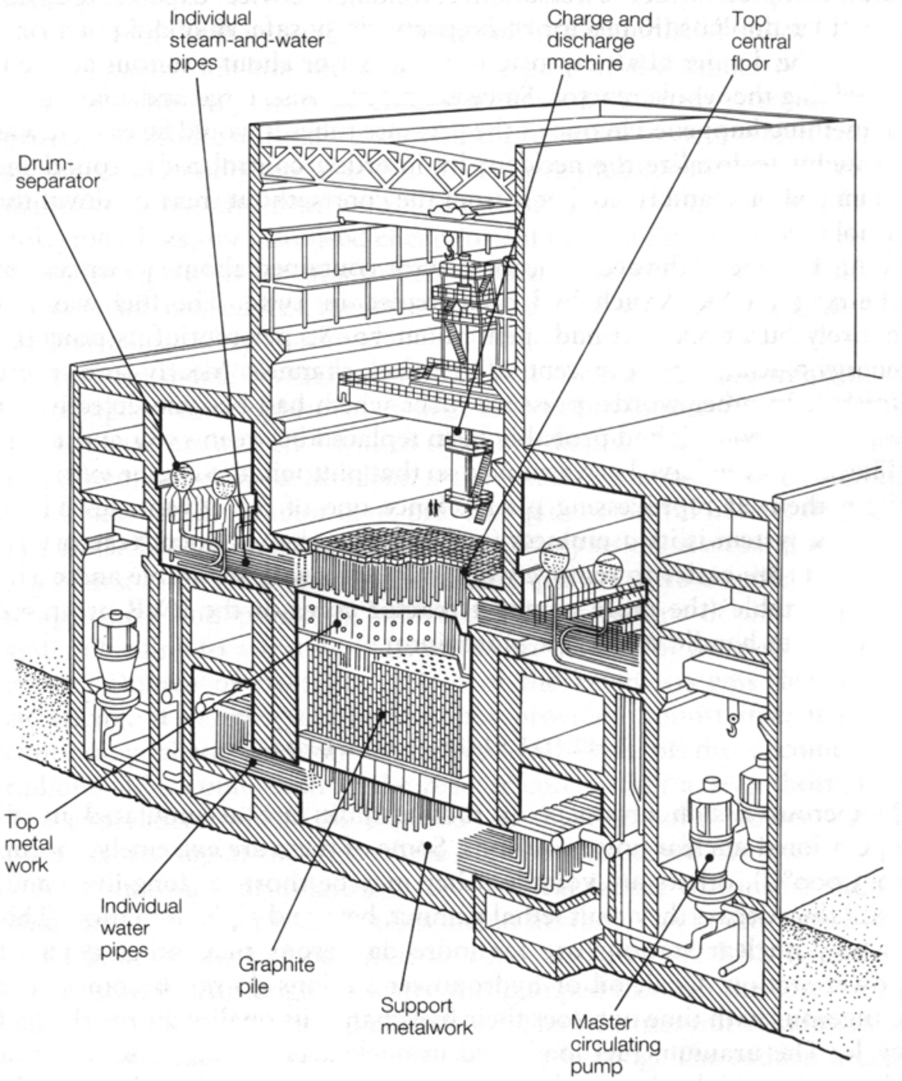

Figure 2. General Overview of the RBMK Reactor [Medvedev:7]

reactors. A reactor of similar design had been used in the USSR for weapons-grade plutonium production [NUREG-1250, Chap 2:1].

The RBMK-1000 reactor has a power rating of 1000 MW(e) (megawatt electric)/3200 MW(t) (megawatt thermal). The core contains 1700 tons of graphite stacked 7 meters high and 12 meters in diameter with 2000 pressure channels for the insertion of 1661 fuel assemblies, 211 control rods, and instrumentation. There is a

requirement for an absolute minimal insertion of 30 control rods to maintain safe operations [OECD:15]. Figure 3 provides a detailed cross-sectional view of the reactor.

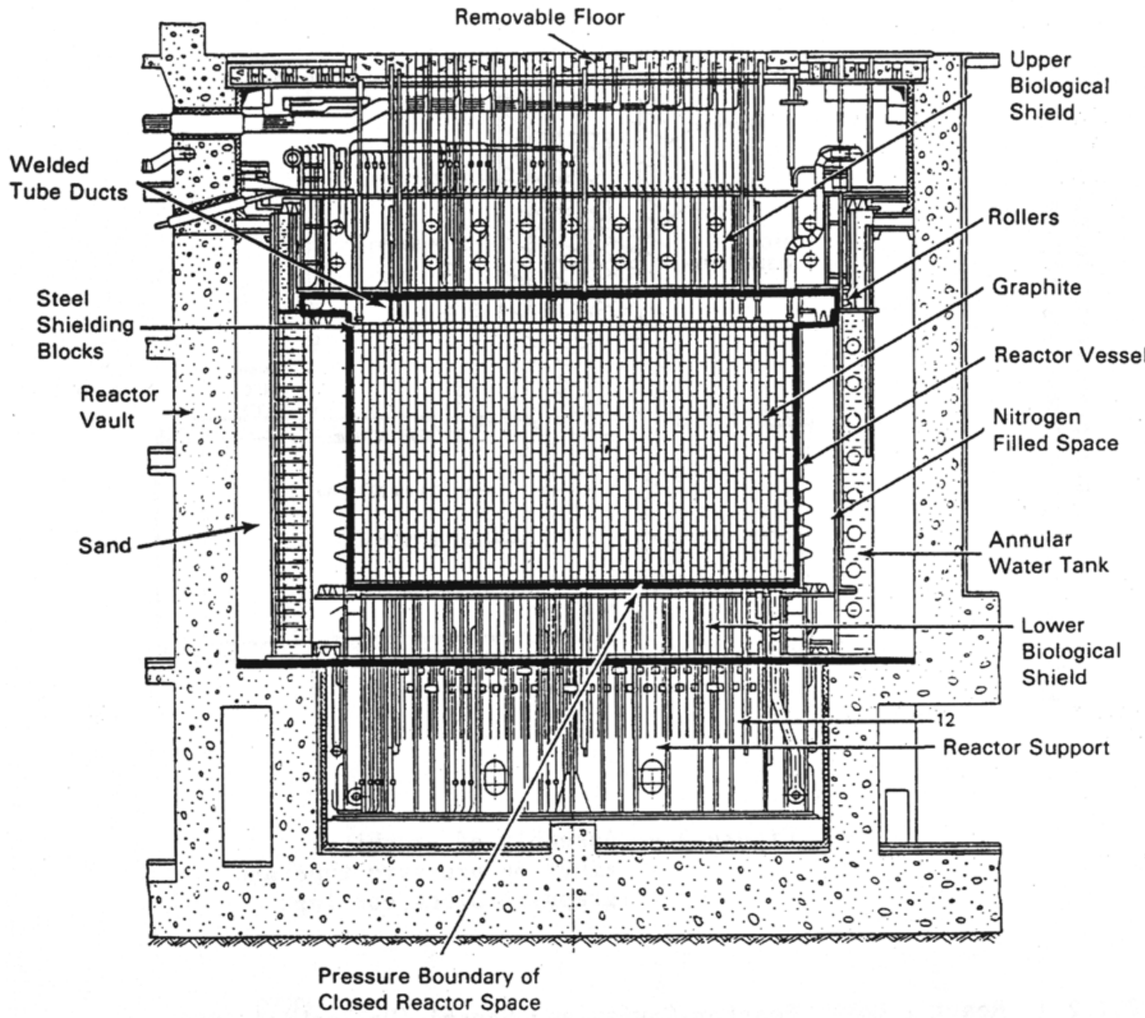

Figure 3. Cross-Sectional View of RBMK-1000 [NUREG-1250, Chap 2:12]

Advantages of this design are on-line refueling and the capability to scale the reactor to ever-larger power ratings. The Soviet Union already had 1500 MW(e) reactors operating and was planning to construct a 2400 MW(e) reactor at the time of the accident [NUREG-1250, Chap 2:3]. Another distinguishing feature involves the separation of the core into two halves, with each side having an independent core cooling system. (Note

the master circulating pumps on each side in Figure 2 on page 9.) This allows shutdown of half the reactor to achieve a 50% power rating. However, compared to Western reactors, there are several disadvantages to this design that contributed to the accident: (1) positive reactivity feedback, (2) lack of a pressure vessel and containment building, (3) slow to respond control rods, and (4) safety systems that could be overridden.

The RBMK reactor design experiences positive reactivity feedback for a coolant void and the graphite temperature, i.e., as these parameters increase reactivity is inserted vice removed. Positive coolant void feedback means that a loss of coolant increases the fission rate of the fuel. (With Western-designed reactors, water serves as the coolant and neutron moderator; hence a loss of coolant results in negative reactivity.) The heat generated in the graphite as a result of moderating the neutrons is removed via the circulating water pumped through channels in the core from the bottom to the top. If the flow rate of the water is reduced or stopped, the temperature rises and the boiling increases. The resulting heat buildup in the graphite inserts additional reactivity. Positive reactivity coefficients, in themselves, are not impossible to control. However, in a core as large as the RBMK, the condition requires good quality instrumentation and control systems to cope with localized disturbances in the power level [Nuclear News, 1986:91]. As a result, unlike water-moderated/water-cooled reactor designs of the United States, the Soviet Union's graphite-moderated reactors are unstable.

The lack of a pressure vessel and containment allowed the release of radioactive material directly to the atmosphere. The primary motivation for the design of the Chornobyl-style reactors was cost, not safety [Marples, 1986:35]. The Soviet Union did not make the same sort of investment in containment as other nations that followed a

Western-type design did. While the reactor core was sealed in a metal container and surrounded by concrete, the rest of the reactor building was constructed of a steel, industrial-standard structure. (Western-designed reactor cores are contained in a steel pressure-vessel.) If a breach of the reactor occurred, there was minimal containment to prevent release of radioactive material into the atmosphere. Despite the lack of a Western-designed containment facility however, it is doubtful that any structure could have contained the force of the explosions from the Chornobyl accident [Medvedev:4].

The slow-to-respond control rods meant that the fission process could not be stopped quickly. Furthermore, the design of the control rods themselves contributed to the accident. Boron, a neutron absorber, was encased in aluminum, with a graphite follower added to the bottom of the control rod. The graphite follower was used to overcome the build-up of water that occurred in the pressure channel when the control rod was fully removed. The graphite follower would displace the water and contribute to the reactivity, unlike the water, which would absorb neutrons. However, it took 15-20 seconds to fully insert the control rod into the core and remove the graphite follower [Knief:306]. Hence, at a time when the fission rate needed to be reduced or halted, the reactivity increased as the graphite follower was slowly pushed out the bottom of the core. Figure 4 is a diagram of the control rods, showing their position in the core when inserted and withdrawn. (Note that when the control rods are fully withdrawn the graphite follower is centered in the core.)

A final, serious design flaw was that no safety systems, including the control rods, operated automatically, independent of the operator [Mould:298]. The ability for an operator to purposely shut down safety systems and put the reactor in an unstable

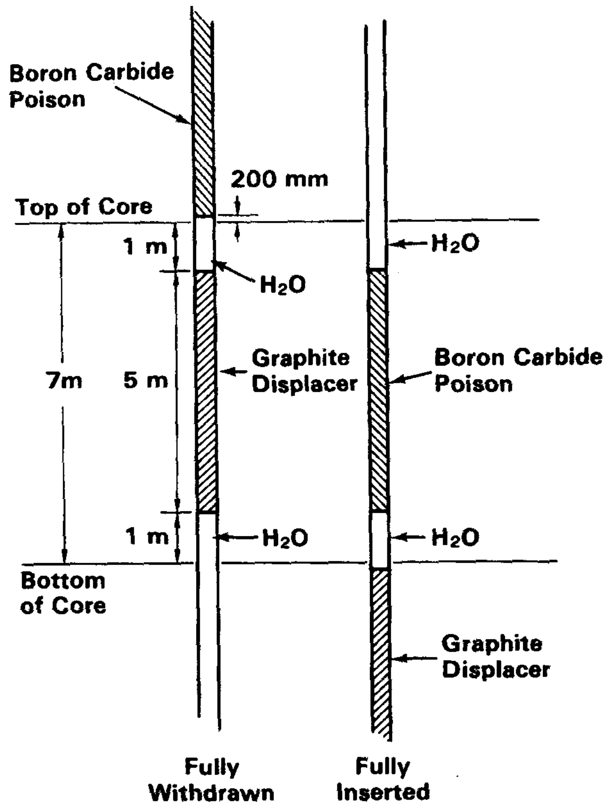

Figure 4. Schematic Drawing of Fully Withdrawn and Fully Inserted Control Rods [NUREG-1250, Chap 2:32]

condition is unheard of with Western-designed reactors. Yet, at Chornobyl the operators purposely shut off emergency cooling systems and disabled emergency shutdown signals in order to carry out a test to validate the safety of the RBMK design. Even in the moments prior to conducting the test, when all indications pointed to an unstable core, the last remaining emergency signal was blocked and the test began [Knief:454].

Account of the Accident

The explosion occurred on Friday, 25 April 1986 at 21:23 GMT (Saturday, 26 April 1986, 01:23 local time). At the time of the accident the reactor operators were

conducting a test of the station's electrical back-up generators. In the event of a blackout at the plant, engineers theorized that the inertia of the now freewheeling, electricity-producing turbines could be used to maintain coolant flow until the emergency generators came online to operate the coolant pumps. This was a concern because the back-up power was supplied by diesel generators which required 15 seconds to come up to full power and drive the coolant pumps [NUREG-1250, Chap 2:37]. This test had been attempted at least twice in the past [Knief:451]. However, this particular test was unauthorized, and was occurring over a weekend, and at night, when supervision at the plant would have been minimal.

At 21:06 GMT, 24 April, shutdown procedures began with the lowering of the control rods into the core. Twelve hours later, at 09:05 GMT, the power level in the reactor dropped to 50%. For the test to take place, the engineers needed the power level to reach 30%, which would have occurred by 16:00 GMT on 25 April. However, because of a need for power, the Soviet electricity authorities in Kiev refused to allow a further reduction in the power level [Mould:34].

With the reactor continuing to operate at about half-power for the next nine hours, xenon-135, a neutron absorber, began to build up in the core. When permission was given to continue the shutdown of the reactor at 19:10 GMT, the power level dropped to 1%, approximately 30 MW(t). This level was inadequate to conduct the test since there wasn't enough power available to turn the coolant pumps and the turbines which required at least 60 MW(e)/180 MW(t) [Medvedev:30]. Rather than abort the test and shut the reactor down, the engineers chose to withdraw 24 of the final 30 control rods in an attempt to increase the power level [OECD:15]. Power rose briefly to 7% (200 MW(t))

by 21:00 GMT. To ensure adequate cooling following the test, all eight coolant pumps were turned on [NUREG-1250, Ch. 4:4]. This resulted in a high flow rate that limited the voiding in the coolant, requiring still further withdrawal of the control rods.

At 21:23 GMT the test began. The engineers realized that the power level was accelerating rather than staying constant as needed for the test. They decided to insert all the control rods that were removed. Because of the design of the control rods discussed earlier, the power level continued to increase. Between 21:23:43 GMT and 21:23:48 GMT (a span of just over four seconds) the power level reached 100 times full power. The resulting heat vaporized the pressurized water, leading to the steam explosion that blew the concrete cover plate off the reactor core. The zirconium cladding of the fuel rods and the graphite of the core, now exposed to steam and air, oxidized, forming hydrogen. This caused a second explosion (of the hydrogen) two to three seconds later that discharged chunks of graphite and fuel out of the reactor building.

An American satellite that had by chance passed over the site in an orbit to monitor missile launches observed the first indication in the West of an accident.

> America's initial assessment was that a nuclear missile had been fired, then when the image remained stationary, opinion changed to a missile had blown up in its silo. It was only when a map of the area was consulted that it was realized that it was the Chernobyl NPP. [Mould:48-49]

On Sunday evening, 27 April, the International Atomic Energy Agency (IAEA) in Vienna was being asked to confirm that an accident had occurred [Mould:49].

Even in the era of Perestroika ("restructuring") and Glasnost ("openness"), initial information from the then-Soviet Union concerning the accident was not forthcoming or

accurate. The first official acknowledgment of an accident occurred on the evening of 28 April with the following announcement on Soviet television:

> An accident occurred at the Chernobyl Nuclear Power Plant as one of the reactors was damaged. Measures are being taken to eliminate the consequences of the accident. Aid is being given to those affected. A government commission has been set up. [Hopkins:38]

By this time the West already had confirmation of the accident, when radiation alarms went off at the Forsmark Nuclear Power Plant in Sweden at 08:00 GMT, 28 April [Medvedev:196]. Initially, plant operators in Sweden feared a leak at their facility. Measurements at other facilities in Sweden provided independent confirmation that the source of the release was inside the Soviet Union.

Core Inventory and Radionuclides Released

The Chornobyl source term has been estimated in several publications and is based on three methods: estimation of the shutdown core inventory of radionuclides and the amount of fuel remaining in the melted core after the accident; studies of the release dynamics during the active phase of the accident; and soil, air and water measurements following the accident [Aarkrog, *et al*.:74]. About one-quarter of the total radioactive material was released during the early stages of the accident, decreasing to a minimum on 1 or 2 May, and then increasing daily until 6 May when the release all but ceased. Source term estimations have improved over time with the pattern being an ever-increasing estimate of the radioactivity released. The 1986 Soviet report on the accident stated that a total of 50 million Curies (MCi), or 1.85E18 Becquerels (Bq), were released with an error of ±50% [UNSCEAR, 1988:306]. This value did not include the release of noble gases that was also estimated at 50 MCi (1.85E18 Bq). Not including noble gases

in release estimates is a common practice, as they are chemically inert, and thus are not reactive and would pass through human tissue without being retained. Figure 5 shows the source term estimation provided by the Soviet Union at the IAEA conference (August 1986) on the accident. The quantities shown in Figure 5 are calculated for 6 May 1986 taking into account radioactive decay up to that date. For example, the 12 MCi shown for

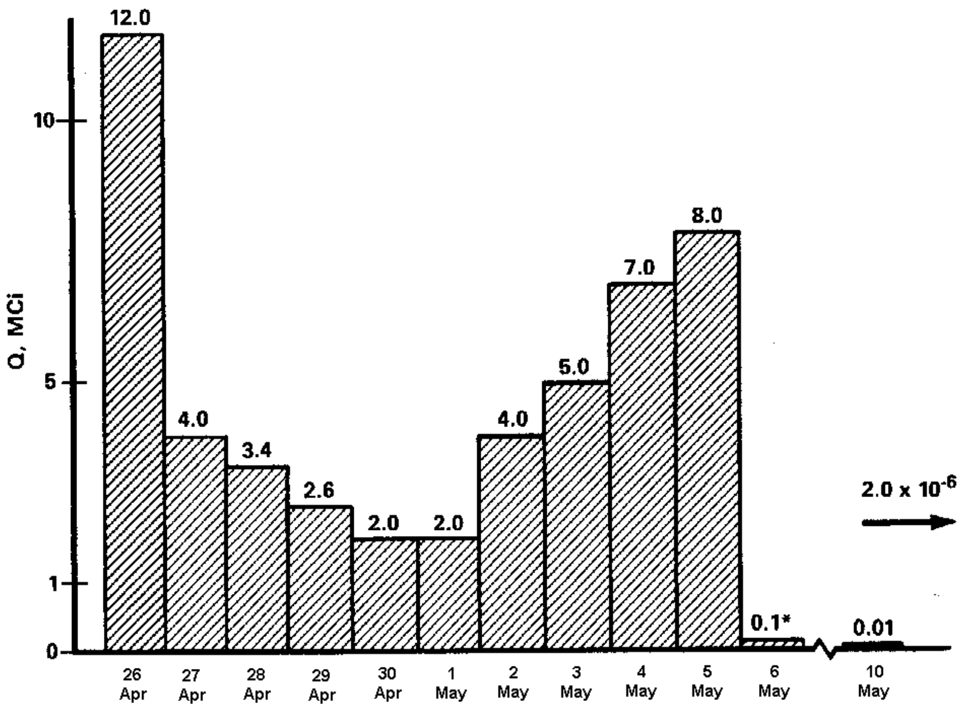

Figure 5. Daily Activity Release From the Chornobyl Reactor, Decay Corrected to 6 May 1986 [NUREG-1250, Chap 6:3]

26 April, when decay corrected from 6 May to 26 April, would result in about 20 MCi for the actual release. The figure does not provide data on the activity release resulting from noble gases, e.g. Kr-85 and Xe-133. Two years after the accident the estimated release was revised upward in excess of 100 MCi (3.70E18 Bq) [Knief:458]. Ten years later, the IAEA estimated the total release, excluding noble gases, to be 143 MCi (5.30E18 Bq)

[UNSCEAR, 2000:518]. Table 2 provides current estimates of the core inventory, and the percent and amount of radionuclides released in the accident.

Table 2. Core Inventory and Total Release of Select Radionuclides

Radionuclide	**Half-life (y=years, d=days)**	**Core Inventory (Ci)**	**% Released**	**Activity Released (Ci)**
Kr-85	10.72 y	8.92E+05	100.0	8.92E+05
Xe-133	5.24 d	1.76E+08	100.0	1.76E+08
I-131	**8.02 d**	**3.51E+07**	**20.0**	**7.03E+06**
Te-132	3.20 d	8.65E+06	15.0	1.30E+06
Cs-134	2.07 y	5.14E+06	10.0	5.14E+05
Cs-137	30.07 y	1.77E+07	13.0	2.30E+06
Mo-99	2.75 d	1.30E+08	4.8	6.24E+06
Zr-95	64.02 d	1.19E+08	4.4	5.23E+06
Ru-103	39.27 d	1.11E+08	2.9	3.21E+06
Ru-106	1.02 y	5.68E+07	2.9	1.65E+06
Ba-140	12.75 d	7.84E+07	5.6	4.39E+06
Ce-141	32.50 d	1.19E+08	2.3	2.74E+06
Ce-144	284.60 d	8.65E+07	2.8	2.42E+06
Sr-89	50.52 d	5.41E+07	4.0	2.16E+06
Sr-90	28.78 y	5.41E+06	4.0	2.16E+05
Pu-238	87.70 y	2.70E+04	3.0	8.11E+02
Pu-239	24065 y	2.16E+04	3.0	6.49E+02
Pu-240	6537 y	2.70E+04	3.0	8.11E+02
Pu-241	14.4 y	4.59E+06	3.0	1.38E+05
Cm-242	162.8 d	7.03E+05	3.0	2.11E+04

Source: Mould, 2000.

From a radiological standpoint, Cs-137 and I-131 are the most important radionuclides to consider in the release from the Chornobyl accident, because they are responsible for most of the radiation exposure received by the general population [UNSCEAR, 2000:456]. Table 3 gives an estimate of the source term determined by the IAEA, World Meteorological Organization (WMO) and the Commission of the European

Communities (EC) from a joint commission studying the atmospheric transport of radiation from the Chornobyl accident.

Table 3. Estimated Release Rates for Cs-137 and I-131 [Klug, *et al.*:358]

From	To	Cs-137	I-131	Effective initial plume centre of mass height
Time day	Time day	(TBq/day)	(TBq/day)	(m)
UTC	UTC			
00.00 26/04	24.00 26/04	2.2 10E + 4	1.9 10E + 5	600(*)
00.00 27/04	24.00 27/04	7.0 10E + 3	5.5 10E + 4	600
00.00 28/04	24.00 28/04	5.5 10E + 3	4.1 10E + 4	300
00.00 29/04	24.00 29/04	4.1 10E + 3	2.8 10E + 4	300
00.00 30/04	24.00 30/04	3.0 10E + 3	1.9 10E + 4	300
00.00 01/05	24.00 01/05	3.0 10E + 3	1.7 10E + 3	300
00.00 02/05	24.00 02/05	5.5 10E + 3	2.8 10E + 4	300
00.00 03/05	24.00 03/05	6.3 10E + 3	3.0 10E + 4	300
00.00 04/05	24.00 04/05	8.1 10E + 3	3.5 10E + 4	300
00.00 05/05	24.00 05/05	8.9 10E + 3	3.6 10E + 4	300
00.00 06/05	24.00 06/05	1.1 10E + 2	7.4 10E + 2	300

The data in Table 3 are consistent with several other publications for the total release of activity from Cs-137 and I-131. This source term is broken into 11 release periods of 24 hours each, with an additional specification that the first release period can be further divided into two release periods; an initial release lasting 6 hours at an effective stack height of 1500 meters and containing 20% of the first day's release, and the second release period of 18 hours at a height of 600 meters containing the remaining 80% [Klug, *et al*:358]. As expected, this detailed source term proved to be more effective in predicting the consequences using HPAC than source terms that simply provided a total release.

Figures 6 through 9 provide midday weather charts for four days during the release period. The movement of the plume can be broken down into three release periods. The early part of the release spread into Poland Scandinavia on 27-28 April. This was followed from 29 April until 2 May by the movement of the plume east into Russia. After 2 May the plume spread to the southwest and west into Europe.

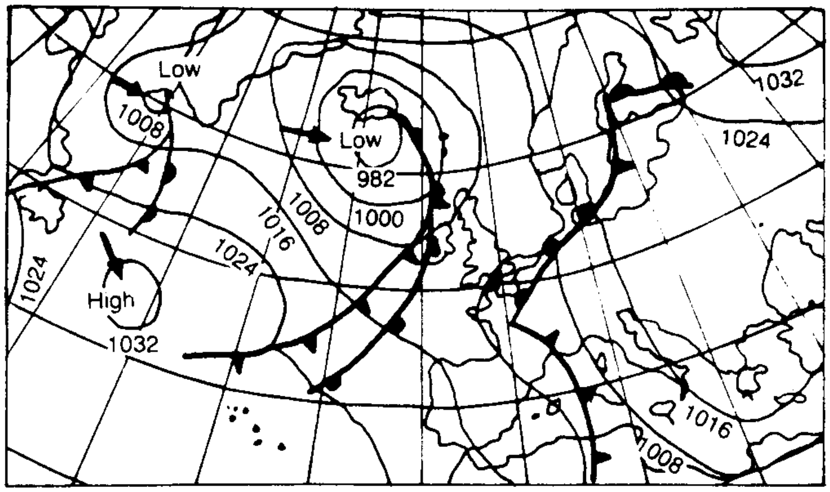

Figure 6. Midday Weather Chart for 26 April 1986 [ApSimon, *et al*:296]

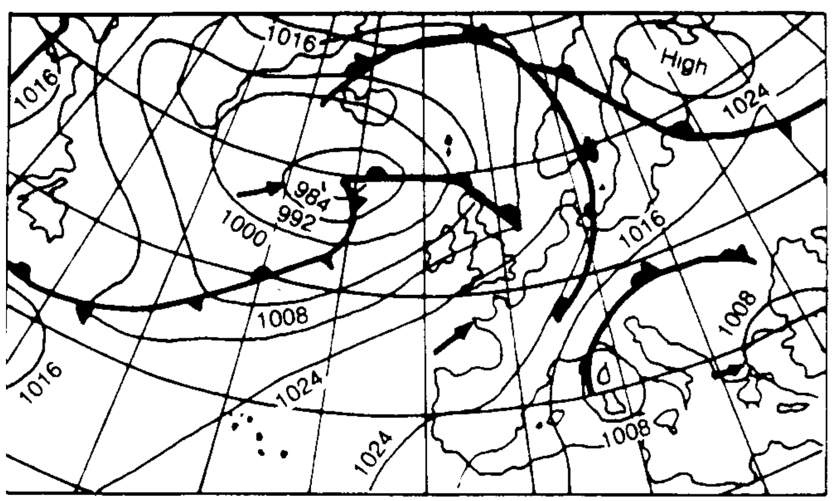

Figure 7. Midday Weather Chart for 30 April 1986 [ApSimon, *et al*:296]

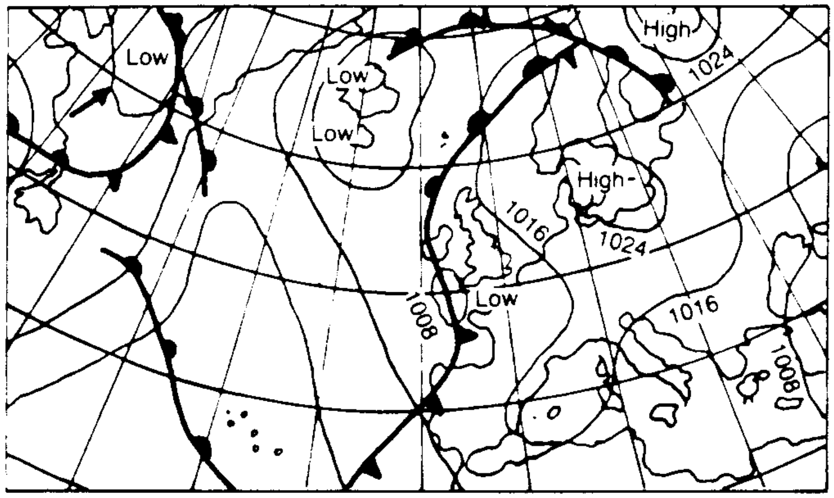

Figure 8. Midday Weather Chart for 2 May 1986 [ApSimon, *et al*:296]

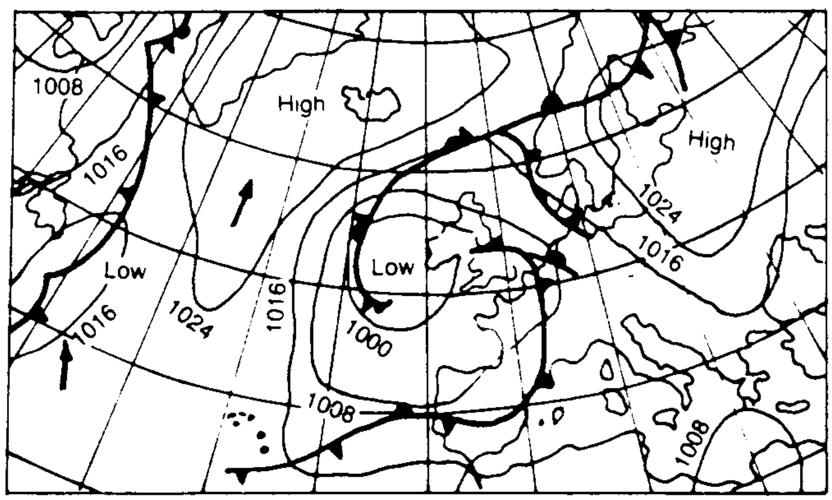

Figure 9. Midday Weather Chart for 5 May 1986 [ApSimon, *et al*:296]

Comparison with Three Mile Island

To place the radioactivity released from the Chornobyl reactor in perspective, it is useful to judge against radioactivity releases from previous nuclear events. Often,

comparisons are made with releases from atmospheric nuclear weapon tests. For example, Eisenbud states that the Cs-137 released from the accident was equivalent to about 3% of the more than 500 atmospheric tests conducted by all nations [Eisenbud:415]. Although this provides an indication of how catastrophic the Chornobyl accident was, it serves as a poor comparison for several reasons. Whereas nuclear weapon tests produced fallout generated by the detonation of fission and fusion devices, the Chornobyl fallout resulted from a conventional explosion of the reactor core. This dissimilarity produces different mixtures of radionuclides making direct comparisons misleading. Additionally, the injection heights into the atmosphere were different and the weapon tests were conducted in isolated locations away from population centers [Aarkog *et al*.:100]. The accident at Three Mile Island also involved a release of material. (However, the release was gaseous material, and not the result of an explosion.)

The accident at Three Mile Island unit #2 (TMI-2), on March 28, 1979, was the worst commercial reactor accident in the United States. It was characterized as a loss of coolant accident (LOCA). The TMI-2 accident began when a pressure relief valve malfunctioned, and conditions worsened when operators incorrectly diagnosed the problem. (In the case of the Chornobyl accident, operator involvement initiated the chain of events that lead to the accident.) The TMI-2 accident resulted in the upper portions of the uranium fuel assemblies melting from the extreme heat and flowing down through the core in the reactor vessel before re-solidifying. Despite the destruction of the fuel, very little radioactive material escaped because the reactor pressure vessel did not fail. Most of the radiation released was attributable to the noble gases xenon-133 and krypton-88. For I-131 the Chornobyl accident released one million times more activity than was

released at TMI, and for all non-noble gas activity released, the Chornobyl accident released ten millions times more activity than did TMI. Table 4 provides a comparison of selected radionuclides released from the Chornobyl and TMI accidents. Table 2 on page 19 provides data on several other radionuclides released from the Chornobyl accident. For the TMI accident the release was limited to "Xe-133 (mostly), Xe-133m, Xe-135, Xe-135m, Kr-88, and traces of I-131" [Frederick:14].

Table 4. Comparison of Releases from TMI and Chornobyl

Radionuclide	Total Released from TMI (Ci)	Total Released from Chornobyl (Ci)
Xe-133	8.30E+06	1.76E+08
Kr-85	N/A	8.92E+05
Kr-88	1.70E+06	N/A
I-131	1.49E+01	4.86E+07
Cs-137	0.00E+00	2.30E+06
Total Release (non-noble gases)	< 1.50E+01	1.43E+08

Sources: UNSCEAR 2000, Mould 2000.

Of note is that following the Chornobyl accident the NRC concluded that no immediate changes were needed in the United States regarding the design and operation of U.S. commercial nuclear reactors [NUREG-1251, Vol. I:2].

III. Description of the HPAC Software and NFAC Incident Model

This chapter provides information on the development of the HPAC software, the procedures used in running the HPAC software for this research, and a discussion of the source term methodology behind the NFAC model execution. Throughout the remainder of the thesis, words and names used in the software are italicized.

Software Origin

The HPAC 3.2.1 software is composed of six incident models that predict the source term for a particular incident. The six models are for incidents involving 1) chemical and biological facilities, 2) nuclear facilities, 3) chemical and biological weapons, 4) nuclear weapons, 5) radiological weapons and 6) nuclear weapons used against a biological facility.

The predecessor to NFAC is the Radiological Assessment System for Consequence Analysis (RASCAL) software developed in 1989 by the NRC to predict the release and consequences of an accident at a U.S. reactor. The RASCAL software predicted the source term from an accident based on the methodology specified in the 1988 NRC Report NUREG-1228 "Source Term Estimation During Incident Response to Severe Nuclear Power Plant Accidents." The software then transported the release using the TADMOD (Transport And Dispersion MODel), developed by Pacific Northwest National Laboratory [Sjoreen, 2001b].

The RASCAL software met a need for DTRA in the early 1990's (then DNA, Defense Nuclear Agency). The source term model developed by the NRC served as one of the incident models in a software program then under DNA development. The TADMOD transport and dispersion model was replaced with SCIPUFF (Second Order

Closure Integrated PUFF), a transport model already developed for DNA. With this software predicting the consequences of not only a radiological incident, but other incidents as well, DNA named their program HASCAL (Hazard Assessment System for Consequence Analysis). Since HASCAL maintained a worldwide database of nuclear facilities, additional research was needed to develop the plant conditions and source term characterizations for the non-U.S. reactors in the database. This included the RBMK reactor design from the Chornobyl accident. This work was done at ORNL and documented in "Source Term Estimates for Commercial Non-U.S. Reactors" [ORNL/TM-13309]. The HASCAL software has been updated and improved several times since its initial release in 1996, and today is known as HPAC.

Using the Software to Define the Chornobyl Accident in NFAC

Upon starting the HPAC software the HPAC startup window (Figure 10) appears. From this screen the analyst can open an existing project, create a new project or view the online help.

Figure 10. The HPAC Startup Window

When *New Project* is selected from the HPAC startup window the *Save As File Control* dialog box (Figure 11) appears for the analyst to name the project file. After providing a project filename and clicking *OK* the user is ready to set up the new project and define the incident.

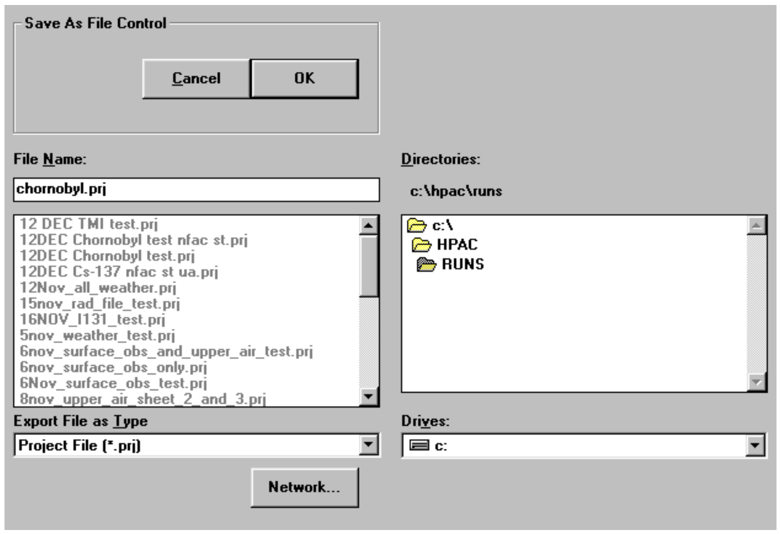

Figure 11. Save As File Control Dialog Box

Figure 12 shows the *New Project Setup* dialog box in which the analyst sets the initial parameters for the project, including the coordinate format in which locations are specified, the reference time used for the project, and the run mode SCIPUFF will use (standard versus fast). When fast mode is selected SCIPUFF relaxes select parameters in order to speed up the computation time [DTRA, 1999:42]. Table 5 lists the differences in the two run modes. The *Dynamics* option specifies whether or not SCIPUFF takes account of buoyancy and momentum rise effects. The *Hazard* option allows weather uncertainty effects to be taken into account in the SCIPUFF calculations. Since weather data of known observations were used in this research the default *Hazard Off* selection

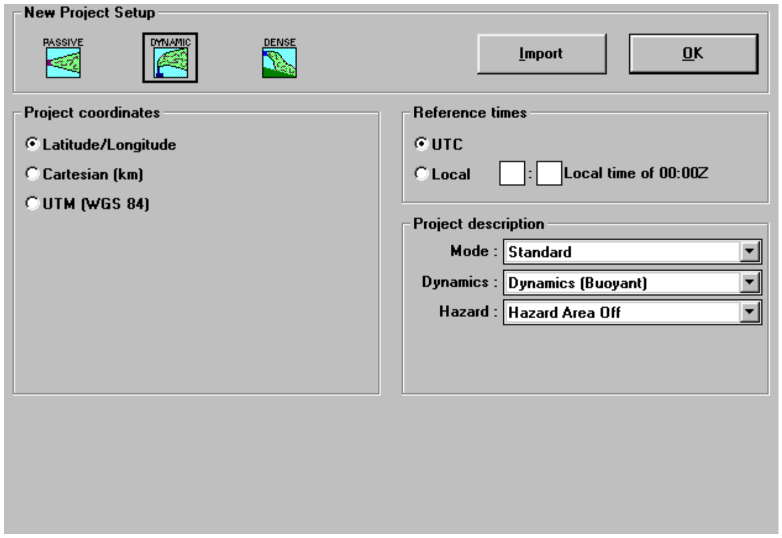

Figure 12. New Project Setup Dialog Box

was used. If required, the user can change the selections during final review of the incident simulation.

Table 5. Difference Between Standard and Fast Run Modes

SCIPUFF Parameter	Standard Mode	Fast Mode
Height of the vertical domain	2500m	5000m
Default vertical domain resolution	250m	1000m
Default maximum vertical grid points	15	7
Horizontal resolution	As needed	1/160th of the domain

Source: Sykes, 2001.

The HPAC software is designed for two types of users, Operational and Analytical. (Both of these are referred to as 'analysts' in this thesis.) Operational users include service members and commanders who need to quickly predict the consequences of an event, and may not necessarily have the technical background to understand the

scientific details of the release being modeled. Analytical users are involved in research and development, and typically want full control of the release parameters available in the *Advanced* edit mode. Figure 13 shows the *New PROJECT Editor* window with the *Operational* edit mode selected. A feature of the HPAC software allows users to toggle between the *Operational* and *Advanced* edit modes as needed. This feature allows a user to modify a scenario that was previously, and quickly, created using the *Operational* edit mode. Selecting the *Audit…* button allows the user to add/change the project metadata, e.g. the title, security classification, analyst's name and creation date of the project.

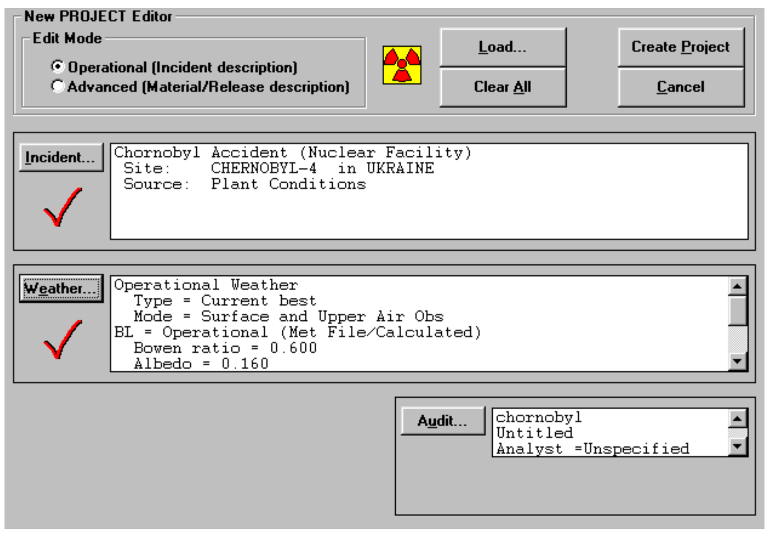

Figure 13. New PROJECT Editor Window (Operational Mode)

When the *Incident…* button is pressed in the *New PROJECT Editor* window the *Incident Control* window (Figure 14) opens to allow the user to define the incident. This window provides a description of the incident scenario. From the *Incident Control* window the user selects *New…* to create an incident. Figures 15 through 27 illustrate the information required for creating an incident involving the RBMK reactor.

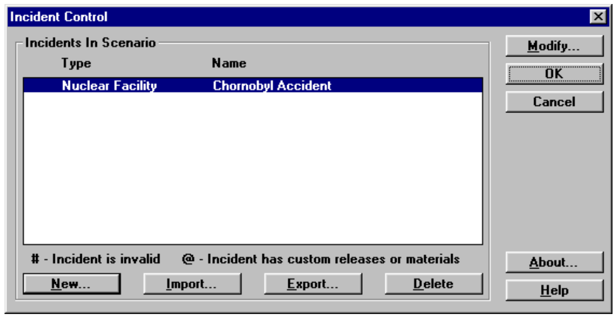

Figure 14. Incident Control Dialog Box

Figure 15 shows the *New Incident* dialog box that allows the user to define an incident using one of the seven incident models available in HPAC. After providing an incident name and selecting the incident type the user presses *Continue…* to define the where, what and when of the incident.

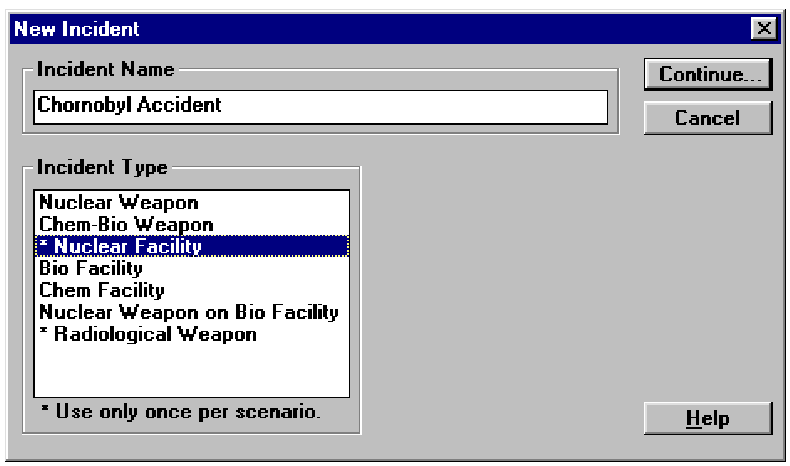

Figure 15. New Incident Dialog Box

Figure 16 shows a completed *Incident Summary* window defining the where, what, when and other options of the NFAC incident. These four are discussed further and illustrated in Figures 17 through 28.

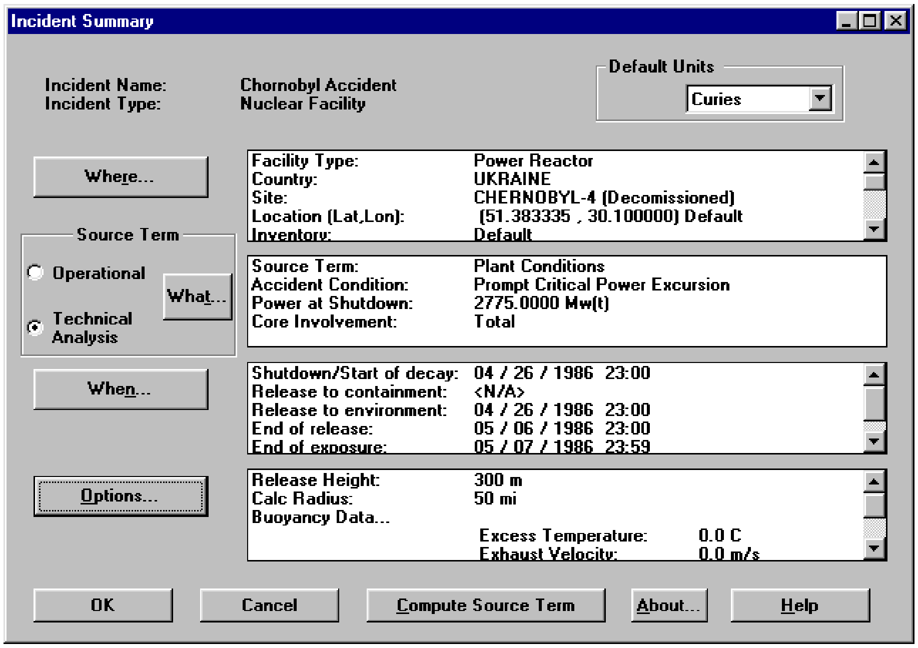

Figure 16. Incident Summary Window

The where of an NFAC incident is defined in the *Site* dialog box (Figure 17). The HPAC software maintains a worldwide database of power reactors, research reactors, and reprocessing facilities. After the user chooses the Chornobyl unit #4 reactor, NFAC selects the corresponding reactor inventory file and determines the reactor's geographic location from the database. Alternately, the user can set the reactor in a different location or provide a custom inventory file. These features allow for modeling facilities with new information that has yet to be incorporated in a software update. Reactors that are no longer operating or are yet to be completed are also maintained in the database. Thus, although Chornobyl unit #4 no longer exists, it is maintained in the database to let HPAC users study the accident.

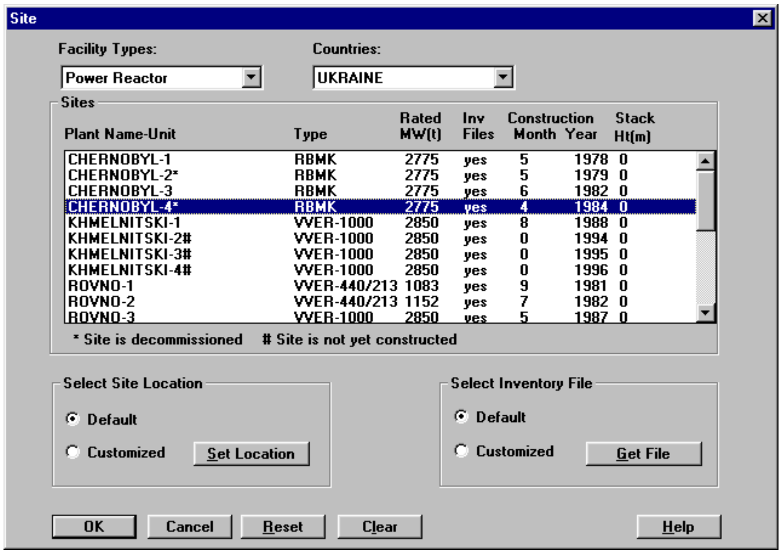

Figure 17. Site Dialog Box

When the user selects the *What* button in the *Incident Summary* window (Figure 16) with the *Operational* radio button selected, the *Operational Mode* dialog box appears (Figure 18). In this mode, the user's only option is to select the severity of the accident. This invokes a predefined source term for the RMBK reactor maintained in an HPAC file. The *Moderate* accident option uses a source term based on a steady-state reactor power of 2700 MW(t) and a long duration release, and the *Severe* accident option uses a source term based on a steady-state reactor power of 2775 MW(t) and a short duration release. A release defined as short duration puts more activity in the atmosphere following the accident, while a long duration results in less activity being released due to radioactive decay of material while it is being held-up in the reactor core. These two options were two of the seven source term specifications modeled in this research. The other five, available in NFAC when the analyst uses the *Technical Analysis* vice the *Operational* option, are discussed next.

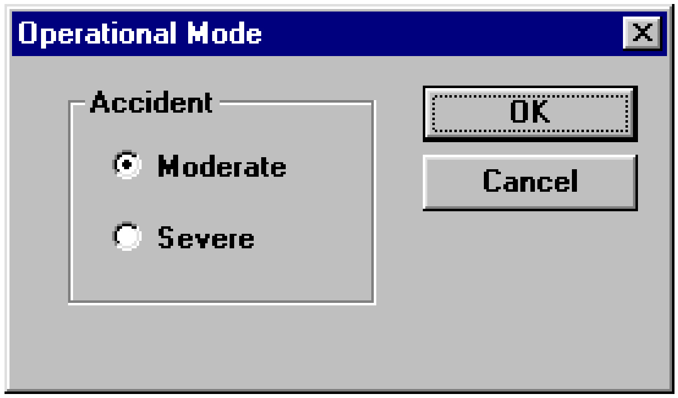

Figure 18. Operational Mode Dialog Box

When the analyst selects the *What* button in the *Incident Summary* window (Figure 16) with the *Technical Analysis* radio button selected, the *Source Term* dialog box appears (Figure 19). This option gives the user more control over the specifics of the source term. For the RBMK reactor, the analyst selects from one of six options in defining the source term. Other reactor designs may have different options available. For example, a light water reactor (LWR) also has an option of *Containment Monitor Reading* to define the source term based on the reading from a radiation monitor located inside the containment. Depending on the option selected, different dialog boxes appear when the *Continue…* button is pressed. Of the six source term specifications listed in Figure 19, only the *Isotopic Concentrations* was not used in this research because it required specifying an activity per unit mass or volume of released material, information not available in the Chornobyl literature. The other five source term specifications available in the *Technical Analysis* option are discussed below.

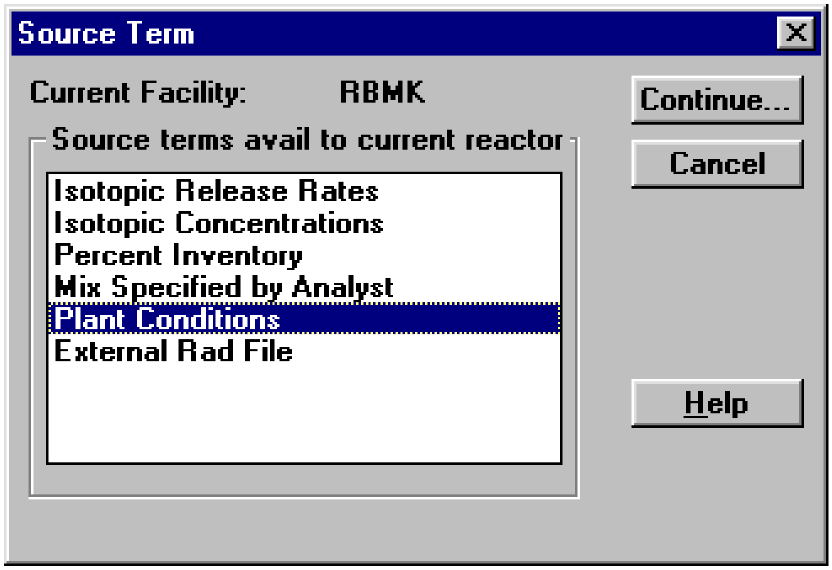

Figure 19. Source Term Dialog Box

Isotopic Release Rates

This source term specification allows the user to specify a release rate for any of the 1040 nuclides maintained in the HPAC database. The ATMES report provided a detailed source term for I-131 and Cs-137 (see Table 3 on page 20). Because of how NFAC handles Cs-137 releases, only I-131 was used. (For Cs-137, NFAC takes into account its short-lived daughter product, barium-137m (Ba-137m), and assumes they are in equilibrium since it grows-in quickly. The resulting source term calculation releases twice as much activity to account for the activity contributed by Ba-137m). Figures 20 and 21 display the dialog boxes the analyst uses to select the atom of interest and the specific radioisotope in order to specify a release rate.

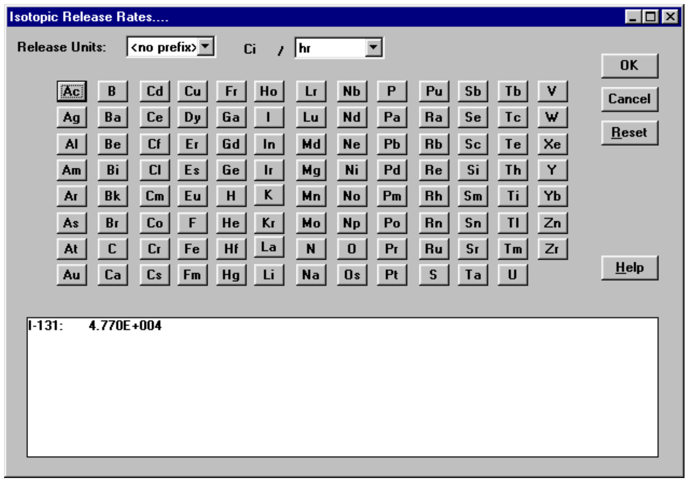

Figure 20. Isotopic Release Rates Dialog Box

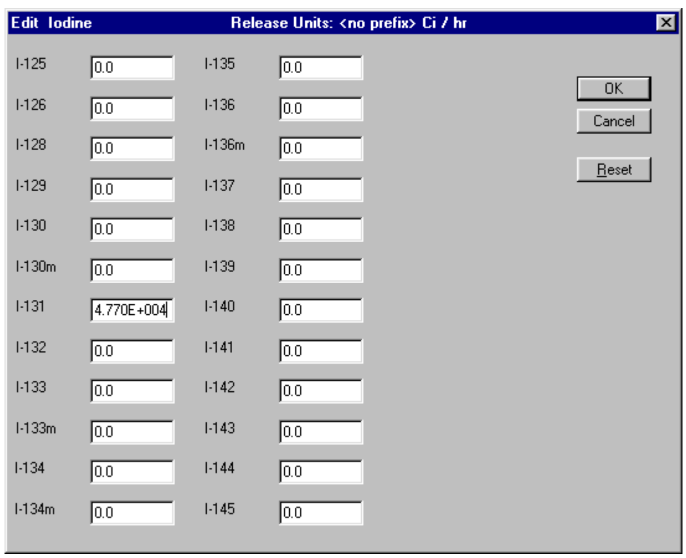

Figure 21. Edit Iodine Dialog Box

Percent Inventory

The Percent Inventory source term specification lets the analyst specify the percent of the total inventory released for each of 12 categories of isotopes, for up to five release periods. Figure 22 displays the *Time Dependent Percent Total Inventory* dialog

box. The analyst can enter different percentages for each time period and vary the length of each of the five time periods. The total of the percentages in all the releases cannot exceed 100. The analyst also specifies the reactor power level. NFAC uses this value to determine the total core inventory. (How the power level is used for determining the core inventory is discussed in the NFAC Source Term Estimation for the RMBK Reactor subsection of this chapter beginning on page 46.)

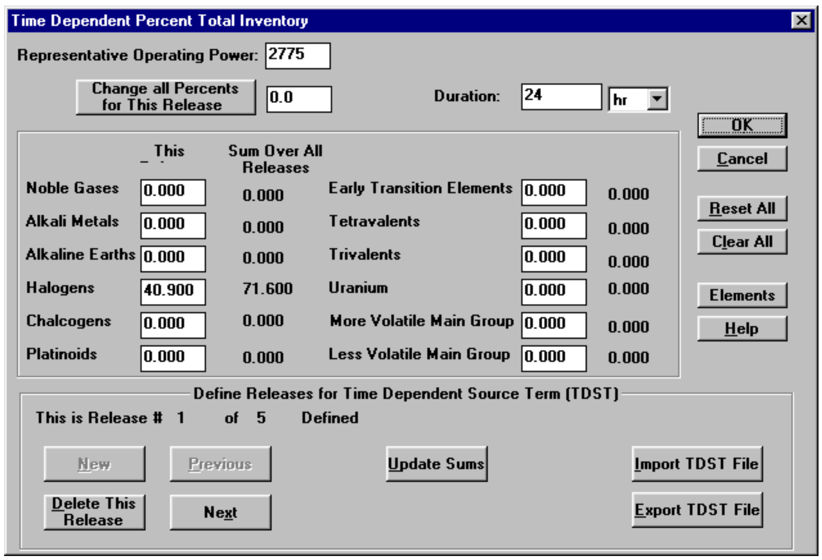

Figure 22. Time Dependent Percent Total Inventory Dialog Box

Mix Specified by Analyst

In this source term specification the analyst provides a gross release rate for the accident (Figure 23) and what percentage of the core inventory is released from each of the 12 categories of isotopes listed in Figure 24. To determine the core inventory, a default reactor power level of 2775 MW(t) is used by this source term specification for the RBMK reactor.

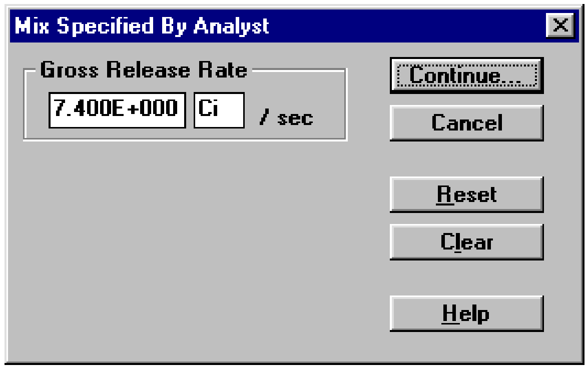

Figure 23. Mix Specified By Analyst Dialog Box

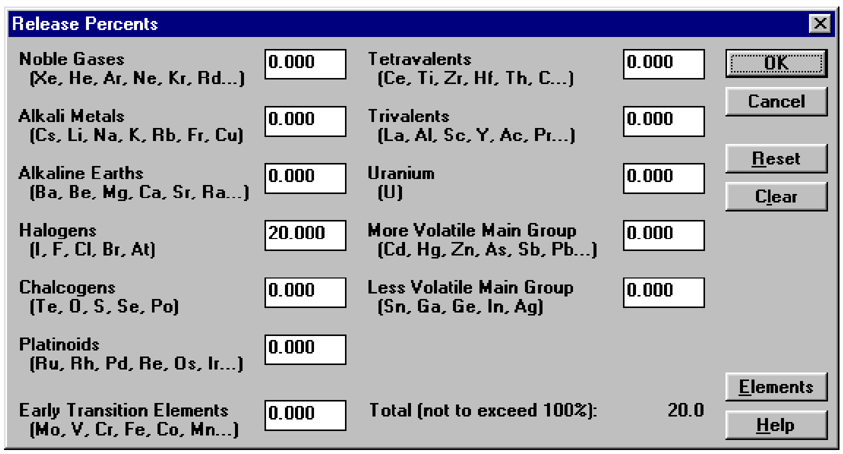

Figure 24. Release Percents Dialog Box

Plant Conditions

A condition unique to the RBMK reactor is that of a prompt critical power excursion, a sudden increase in reactivity that causes the power to rise promptly, resulting in intense steam formation, an abrupt increase in pressure, and subsequent steam explosion that shatters the reactor. This is one of three release pathways available for the plant conditions, displayed in Figure 25. The other two release pathways, *Confinement*

Leakage/Failure and *Confinement Bypass*, were not applicable in describing the release pathway for the Chornobyl accident and therefore were not used.

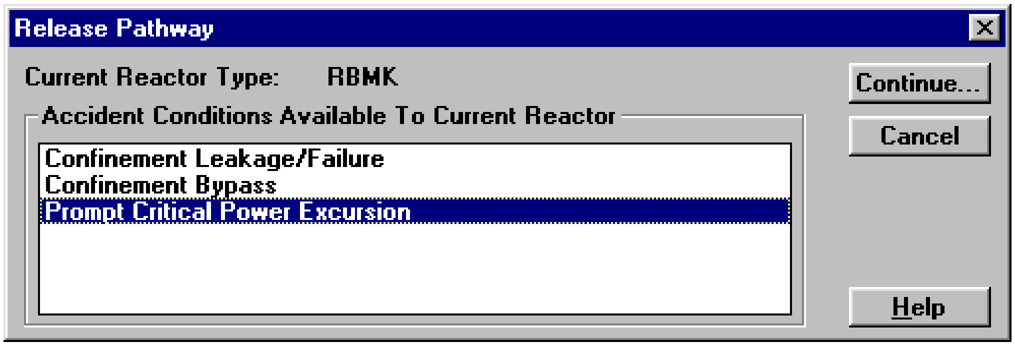

Figure 25. Release Pathway Dialog Box

When the *Prompt Critical Power Excursion* plant condition is selected the user has to provide the representative operating power and core involvement in the accident (Figure 26). The representative operating power is the steady-state power of the reactor prior to shutdown. The design of the RBMK reactor allows for on-line refueling and shutdown of a portion of the reactor. Thus the option to select the core involvement is included.

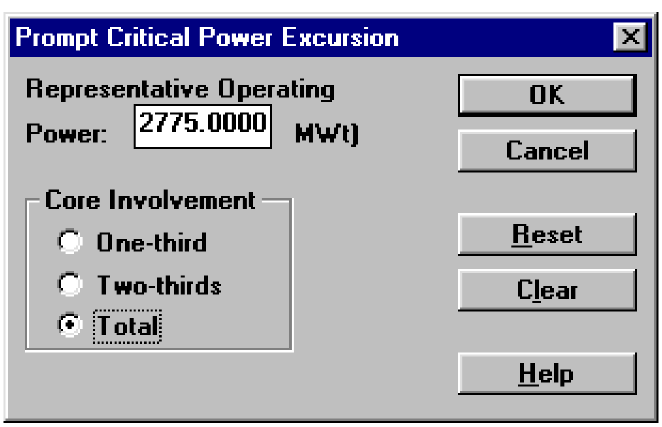

Figure 26. Prompt Critical Power Excursion Dialog Box

External Rad File

The *External Rad File* specification allows the analyst to import a source term computed by a different model or prepared by the user in a text editor. The advantage of the external Rad file is that the analyst can provide more detailed information about the release than NFAC can in computing the Rad file internally. Appendix A provides information on the Rad file preparation. This completes the discussion of the source term specifications in defining the "what" of the accident.

Figure 27 shows the *Events* dialog box that allows the user to define the "when" of the accident. Depending on the options selected in defining the "where" and "what" of the accident, the user may not be able to define all five of the times used to describe an accident. For example, the Chornobyl reactor did not have a containment structure, therefore a *Release to Containment/Confinement* time cannot be specified; or, if an external Rad file is used, then the *End of Release* cannot be specified, and instead is

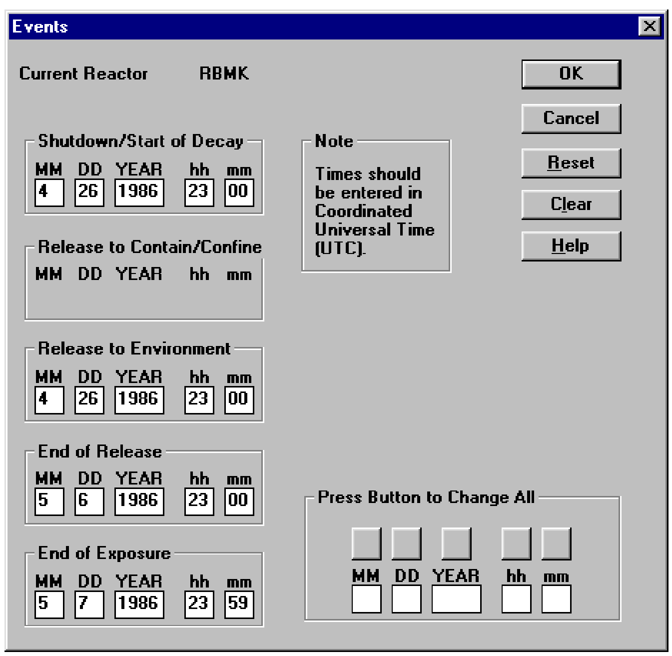

Figure 27. Events Dialog Box

calculated based on the *Release to Environment* time and the release duration specified by the user in the Rad file. The *End of Exposure* time is the time when SCIPUFF will stop its calculations, including radioactive decay of the release.

The final button available in the *Incident Summary* window (Figure 16) is the *Options* button. The *Calculation Options* dialog box is shown at Figure 28. The user may enter additional information relating to the NFAC incident. Of special note is the *Release Height* option. In the case of the Chornobyl accident, the radioactive plume was injected into the atmosphere before it began following the ambient air motion. For example, the ATMES source term gives a release height that varied from 300-1500 meters during the release [Klug, *et al*.:358]. NFAC only allows one release height value for the duration of the release. The *Calculation Radius* option sets the radius from the reactor for which SCIPUFF will conduct transport and dispersion calculations. This

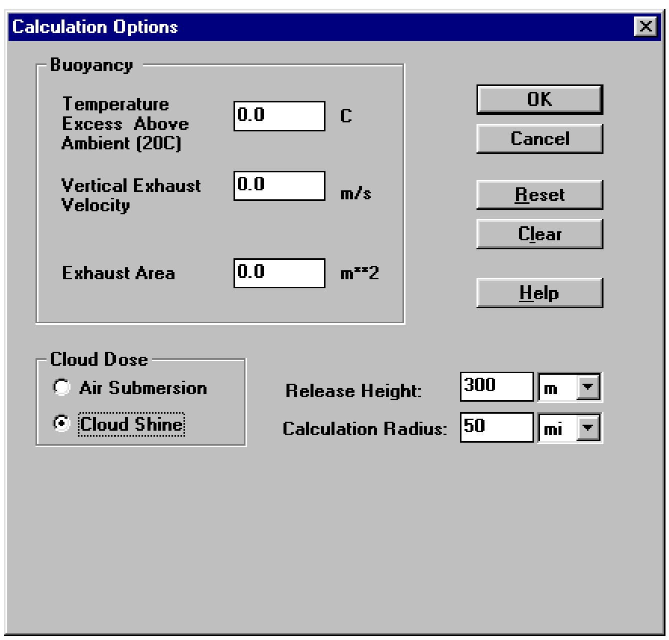

Figure 28. Calculation Options Dialog Box

is one of two ways to select the spatial domain. The other is available in the *Advanced* edit mode and will be discussed as part of Figure 30 (page 42). The *Cloud Dose* selection allows the analyst to choose how the dose from the radioactive cloud is computed. The *Cloud Shine* option is more accurate than the *Air Submersion* option.

When the *Weather* button is selected in the *New Project Editor* window (Figure 13 on page 29) the *Weather Editor* window opens. Figure 29 shows the *Weather Editor*.

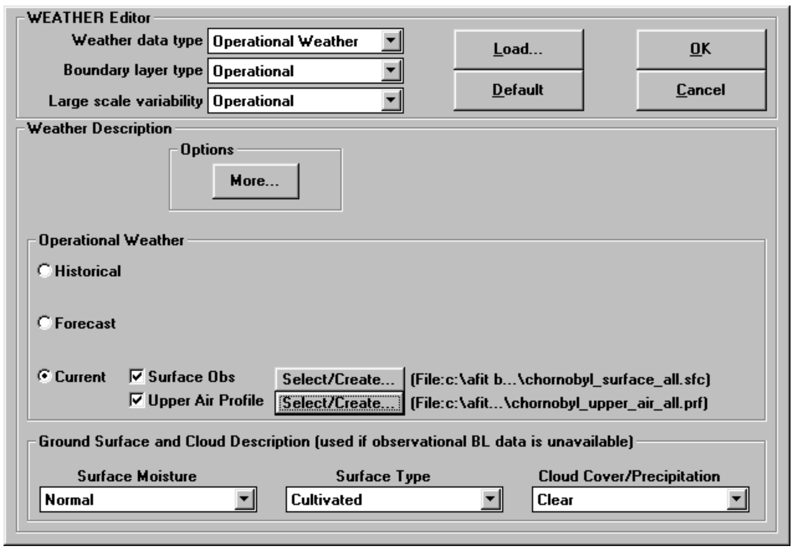

Figure 29. WEATHER Editor Window

HPAC supports several weather data formats. For this research, upper air profile and surface observation data were obtained from AFCCC and prepared in the necessary format. Appendix B provides further information on the weather files used.

Once an incident is defined in the operational edit mode, the analyst can toggle to the *Advanced* edit mode. Figure 30 shows the *New PROJECT Editor* window when the *Advanced* edit mode is selected. This edit mode allows the analyst to refine incident parameters set as defaults in the *Operational* edit mode. The *Release…* and *Material…*

buttons allow the analyst to view or edit the release and material data that are calculated after the analyst specifies the "what" of the accident. The *Time…* and *Domain…* buttons provide "when" and "where" information, respectively, and can also be edited. The *Audit…* button allows the analyst to view or edit information that was input at the start of the project in the *New Project Setup* dialog box (Figure 12 on page 28). For this research two parameters that were changed were the spatial domain and the intervals of the SCIPUFF outputs. Radiation from the Chornobyl accident was measured across Europe,

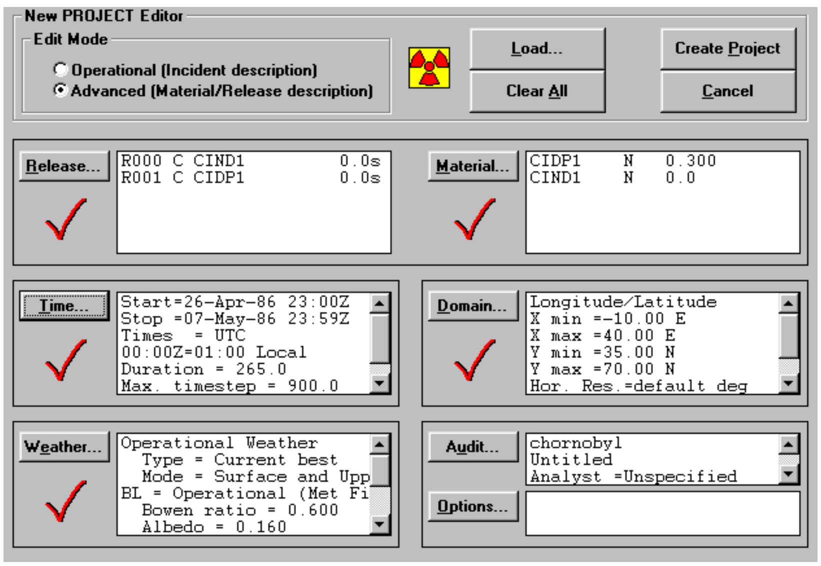

Figure 30. New PROJECT Editor Window (Advanced Mode)

so the spatial domain was changed to encompass Europe in order for SCIPUFF to perform calculations throughout Europe. This is the second way an analyst can define the spatial domain; the first is specifying the *Calculation Radius* in Figure 28.

Once the user has defined the project, the *Create Project* button on the *New PROJECT Editor* window is pressed to begin the transport and dispersion of the source term. Figure 31 shows the SCIPUFF *Run Control* window that provides a status of how

far along the program is in performing its calculations. For this research, SCIPUFF calculations took upwards of 3 hours when HPAC was run in standard mode. Fast mode runs took one-third to one-half the time.

Following completion of the SCIPUFF calculations the *Plot Control* window (Figure 32) is automatically displayed to allow the analyst to view customized plots. The *Plot Control* window also allows analysts to copy plots to the Windows Clipboard;

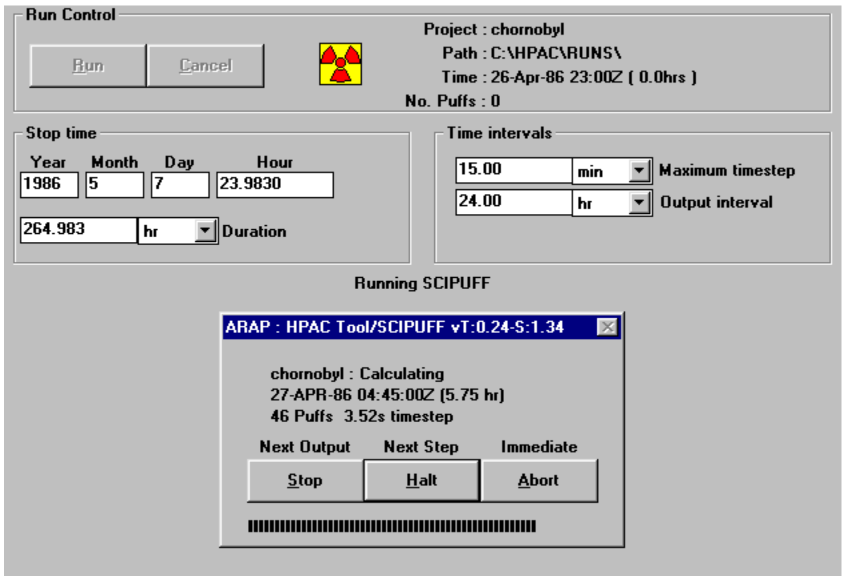

Figure 31. SCIPUFF Run Control Window

export images as bitmap files; animate a series of plots over the calculated output interval; and get dose and dose rate information at specific geographic locations, saving the data to an ASCII text file as a table.

Description of NFAC Material

NFAC materials are defined as either a depositing gas or a non-depositing gas for the purposing of transporting in SCIPUFF. Releases from an accident that take the form of a

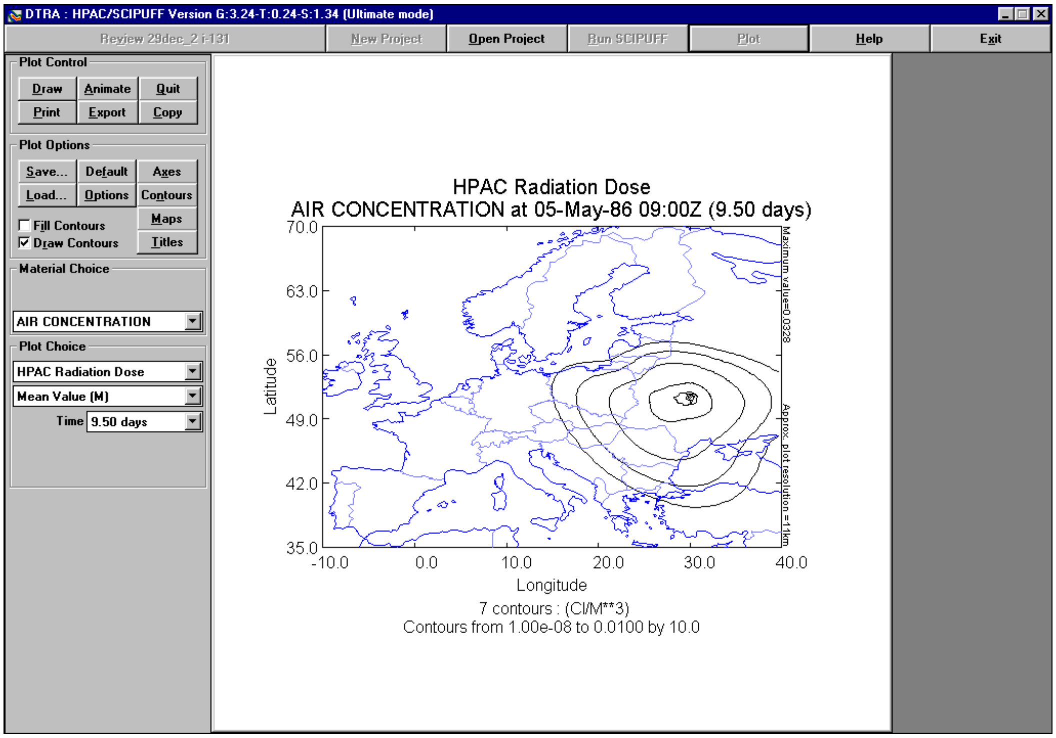

Figure 32. Plot Control Window

gas can be represented as depositing and/or non-depositing gas NFAC materials. Particulate releases are represented as a depositing gas NFAC material. An early design decision made all NFAC materials 1 micron in diameter because of the uncertainty in determining the size of particles released in a reactor accident [Sjoreen, 2001b]. Because of this limitation the analyst cannot define a particle size distribution for transport in SCIPUFF. Since most of the released radioactive material from the Chornobyl accident was in particulate form, an analyst might expect the performance of the HPAC software to be hindered.

Limitations in Plotting Output Data

HPAC is limited to 101 time displays in the plot window. This must be taken into account when recording output from the SCIPUFF runs involving several days of

transport and dispersion. For modeling purposes, the release began at 21:00 GMT on 25 April, and ended at 21:00 GMT on 6 May. The 11 days of transport required recording outputs every three hours, which resulted in recording 88 outputs. Changing the output intervals does not affect the calculations, but does change the times at which the results are available for the analyst to plot. Most of the observed measurements of I-131 air concentrations that will be discussed in Chapter IV were taken at times that were available for plotting. Those times fell on the three-hour intervals for the outputs. However, measurements taken at different times required plotting the output of the nearest time. There was never more than an hour difference between the observed measurement time and the HPAC plotted time.

Use of Weather Files

The Air Force Combat Climatology Center (AFCCC) provided the weather data. It consisted of upper air profile and surface observation data files. The upper air profile data was obtained at six-hour intervals beginning at 18:00 GMT on 25 April, and ending at 06:00 GMT on 7 May. Although it varied from time period to time period, there were about 119 observations taken each time period. The observation points were scattered throughout Europe, with the greatest concentration located in the west. The surface observation data had much greater spatial and temporal densities. Upwards of 400 weather stations provided surface data for the domain of the research, and readings were recorded as often as every 15 minutes for a few of the stations. Since HPAC can only process up to 400 surface observation data points per time interval, selected surface observations from the southwestern corner of Europe were deleted, since this area was least affected by the transport of radioactive material during the release period.

Typically, surface observation data alone are used only when dealing with small domains (less than 200 km, or releases that do not exceed 500 m AGL). Upper air profile data are used when the domain is on a continental scale and release heights are greater than 500 m. Upper air data typically contains data near ground level, thus surface observation data is not needed.

This concludes the description of basic inputs into the NFAC module, and outputs from the HPAC software. The remainder of the chapter will describe the source term estimation methodology employed by the NFAC incident model for an accident involving the RBMK reactor.

NFAC Source Term Estimation for the RBMK Reactor

As with all the modules available in HPAC, NFAC is a source term model. In modeling a nuclear facility accident it determines the activity of the radioisotopes released (the source term) based on user-provided conditions. This source term is then transported through the atmosphere and dispersed via the SCIPUFF model in HPAC. An alternative to having NFAC calculate the source term is for the user to define the material released by providing an isotopic release rate, a percent of the inventory released, or a customized external file (Rad file).

NUREG-1228 describes the methodology for estimating the source term, and is supplemented with ORNL/TM-13309 for non-U.S. reactors. For estimating the source term, the main difference between U.S. and non-U.S. reactors is the characterization of the systems and methods that act to reduce the released fission products from entering the environment [ORNL/TM-13309:2]. These differences are due to the availability of engineered safety systems, such as filters, sprays, containment structures and suppression

pools. For example, rather than using a containment structure, the RBMK reactor uses an accident localization system.

Catastrophic reactor accidents, by their very nature, make determining the source term very difficult. The result is that for a severe accident "there is little hope of actually predicting the source term; only approximations of the source term with large uncertainties can be produced" [NUREG-1228, Ch. 1:2]. With this in mind, the remainder of the chapter presents information on how NFAC predicts the source term for an accident involving the RBMK reactor.

Table 6 gives the seven methods by which the source term can be specified in NFAC for the RBMK reactor. Which method to use depends on the type(s) of information known about the accident. The first five are considered user-defined source terms because the user specifies the material and how it is released. The remaining two are considered NFAC-generated source terms because the user does not specify what is released, but instead indicates the condition of the plant or the severity of the accident. NFAC then calculates the source term based on the user's input regarding the accident condition.

NUREG-1228 outlines a four-step process for estimating the accident source term. The first step is to determine the reactor inventory of fission products. Based on the Chornobyl accident, Morris of ORNL developed a specific plant inventory for an RBMK reactor [Sjoreen, 2001a]. The inventory file is an ACSII text file named *CHERNOBL.1T4*. The 1T4 extension was to remind HPAC developers the inventory file was for reactors 1 to 4 [Sjoreen, 2001a].

Table 6. NFAC Source Term Specification

Method of Source Term Calculation	Description of Method
Isotopic Release Rates	Specify the amount of radioactivity released per unit time for any of 1040 radionuclides
Isotopic Concentrations	Specify the amount of radioactivity released per unit volume of material released and the release rate of the unit volume for any of the 1040 radionuclides
Percent Inventory	Specify the percent of the core inventory released, varying the release over 5 release start times (NFAC limited)
Mix Specified by Analyst	Gross release rate is specified, e.g. 1 MCi over 1 hour, and composition of the release is then specified
External RAD file	Source term and dose factors are computed external to HPAC software
Plant Conditions	Accident conditions are known; e.g. prompt critical power excursion
Operational	Accident is classified as a *Moderate* or *Severe* accident and default source term file is used

The inventory is expressed in Ci/MW(t), so that the specific inventory is calculated by multiplying the inventory values by the long-term steady-state thermal power level of the reactor at the time of the accident. Table 7 lists the inventory of the reactor for some of the prominent radionuclides, as well as the specific inventory of the radionuclides given a long-term steady-state power level of 2775 MW(t). This power level value is used by NFAC for the *Severe* accident option available in the *Operational* mode for defining the source term. The radionuclides listed are typical of the ones provided by agencies that estimated the core inventory of the RBMK reactor at the time of the Chornobyl accident, thus making comparisons between inventories developed by different agencies easier. The specific inventory that was determined using the power rating for a *Severe* accident compares favorably with estimates presented in Chapter II

Table 7. Select Radionuclides from CHERNOBL.1T4 Database File

Fission Product	RBMK Inventory (Ci/MW(t))	Inventory for 2775 MW(t) Power Level (Ci)	Core Inventory from Table 2 on Page 19 (Ci)
Kr-85	3.10E+02	8.60E+05	8.92E+05
Xe-133	4.89E+04	1.36E+08	1.76E+08
I-131	2.35E+04	6.50E+07	3.51E+07
Te-132	3.36E+04	9.32E+07	8.65E+06
Cs-134	2.66E+03	7.38E+06	5.14E+06
Cs-137	3.32E+03	8.94E+06	1.77E+07
Mo-99	4.44E+04	1.23E+08	1.30E+08
Zr-95	4.17E+04	1.16E+08	1.19E+08
Ru-103	3.59E+04	9.96E+07	1.11E+08
Ru-106	1.24E+04	3.44E+07	5.68E+07
Ba-140	4.23E+04	1.17E+08	7.84E+07
Ce-141	4.02E+04	1.12E+08	1.19E+08
Ce-144	3.20E+04	8.88E+07	8.65E+07
Sr-89	2.45E+04	6.80E+07	5.41E+07
Sr-90	2.50E+03	6.94E+06	5.41E+06
Np-239	4.64E+04	1.29E+08	N/A
Pu-238	3.41E+01	9.46E+04	2.70E+04
Pu-239	8.68E+00	2.41E+04	2.16E+04
Pu-240	1.73E+01	4.80E+04	2.70E+04
Pu-241	2.88E+03	7.99E+06	4.59E+06
Cm-242	9.50E+02	2.64E+06	7.03E+05

(see Table 2 on page 19), indicating that 2775 MW(t) is a good estimate of the long-term steady-state power level prior to the shutdown of the reactor.

The second step in determining the source term is to estimate the fraction of the inventory released from the core. NUREG-1228 describes this for U.S. commercial reactors. In compiling the HPAC worldwide database of reactors, ORNL developed the plant damage conditions and source term characterizations for non-U.S. commercial reactors to supplement NUREG-1228. These are documented in ORNL/TM-13309. Table 8 gives examples of the release fractions for core accidents involving the RBMK.

The values originate from NRC studies of reactors and accidents. The first three core conditions are based on a Western-designed BWR and are similarly named [Morris:5].

Table 8. Select Release Fractions for RBMK Core Conditions

Core Condition	Severity Definition	Fission Product	Fraction Released From Core
Gap Failure	Core uncovered less than 30 minutes	Noble gases, Cs, I	0.05
In-Cavity Tube Rupture	Core uncovered more than 30 minutes/less than 1 hour	Noble gases I Cs Te, Sb Ba, Sr Ce, Np Mo, Ru La, Y	1.00 0.30 0.25 0.05 0.02 0.0005 0.0025 0.0002
Reactor Cavity Failure	Core uncovered 1 hour or more	Noble gases I, Cs Te, Sb Ba, Sr Ce, Np Mo, Ru La, Y	1.00 0.70 0.301 0.12 0.0055 0.005 0.0052
Prompt Critical Power Excursion	Uncontrollable insertion of reactivity involving total core	Noble gases I, Te, Sb Cs Ba, Sr Ce, Np, La, Y Mo, Ru	1.00 0.60 0.40 0.06 0.035 0.04

Source: ORNL/TM-13309.

The *Prompt Critical Power Excursion* was determined from studying the Chornobyl accident [Morris:5]. However, note that for the *Prompt Critical Power Excursion* 60% of all the iodine is released from the core. In contrast, the best current estimate for the Chornobyl release is 20% (see Table 2 on page 19).

The third step in predicting the source term is to estimate what fraction of the remaining source term is removed on the way to the environment. Reduction

mechanisms that are capable of removing fission products include particulate filters, pools of water, sprays, and natural processes [NUREG-1228, 1988, Chap 1:10]. However, none of these reduction mechanisms are available for the Chornobyl source term. Since the reactor building was constructed to industrial standards, with thin steel walls and roof, and not to Western-standards with thick reinforced concrete containment, the explosive forces allowed for radioisotopes to immediately enter the environment rather than be held-up and decay.

The final step in predicting the source term is to estimate the amount of the available fission product inventory with potential for release to the environment. Again, because of the design of the RBMK reactor, all fission products with potential for release to the environment are released.

The NRC equation for calculating the source term is defined in NUREG-1228 as:

$$SourceTerm_i = FPI_i \times PowerLevel \times CRF_i \times (\prod_{j=1}^{n} RDF_{ij}) \times EF_i \tag{1}$$

for each radionuclide i and n reduction mechanisms, where

SourceTerm$_i$ = activity of radionuclide i contributing to the source term (Ci)
FPI$_i$ = fission product core inventory of radionuclide i normalized to power (Ci/MW(t))
PowerLevel = long-term steady-state power level at time of the accident (MW(t))
CRF$_i$ = fraction of radionuclide i released from the core
RDF$_i$ = fraction of radionuclide i released from the core remaining after n reduction mechanisms
EF$_i$ = fraction of radionuclide i remaining after the n reduction mechanisms that is released to the environment

Examples of core release fraction (CRF) values for various radionuclides are given in Table 8 (page 50). The assumption that the total effectiveness of the RDFs can be estimated by multiplying them together is suspect [NUREG-1228, Chap 4:2]. This is

because the various reduction mechanisms (e.g. pools of water, sprays, or natural processes) may be acting on the same form of a radionuclide [NUREG-1228, Chap 4:2]. Although this is a concern for most reactor designs, for the Chornobyl accident there were no reduction mechanisms or containment available, thus the *RDF* and *EF* values are 1.0.

IV. Results and Data Comparisons

This chapter begins with a discussion of the tests performed using the HPAC software. The results of the HPAC tests are then displayed in data tables and contour plots. A discussion of how these results compared with the measured data, and how the overall HPAC predictions compared with select models studied in the ATMES report is presented.

Tests Performed and Test Matrix

The test runs performed in this research are listed in Table 9. They are divided into two distinct groups. The first group of tests is prefixed with an "N" in Table 9 and is used to identify NFAC-generated source terms. The second group is prefixed with a "U" to identify the tests as user-generated source terms. Except when noted in the table, the default input parameters for the tests included a stack height of 300 meters, the standard run mode, measurement of the I-131 air concentration at 2 meters above the ground, and a 2775 MW(t) power level.

The NFAC-generated source term runs primarily served as a "what if" test to determine how well the HPAC software would predict the Chornobyl accident if it was to happen now. For this scenario the analyst would not have any detailed information concerning the activity released and thus would use the software to generate the source term. These runs used the actual weather data for Europe that was provided by AFCCC. Even though actual long-term, detailed weather data would probably not be available for the analyst if an accident has just occurred, the AFCCC archived weather is used here to limit/eliminate poor weather data as a source of error in the predictions. (The analyst would be able to get forecast data from the DTRA meteorological data server.)

Table 9. Test Matrix

Test ID	Source Term Specification	Release Period	Total Release	Weather Data	Notes
N-1A	Plant conditions, prompt critical power excursion, total core	4/25 2100 to 5/6 2100	39.1 MCi	Upper air and surface	
N-1B	Plant conditions, prompt critical power excursion, total core	4/25 2100 to 5/6 2100	45.2 MCi	Upper air and surface	3200 MW(t) power level
N-2	Severe accident	4/25 2100 to 4/27 0300	44.2 MCi	Upper air and surface	
N-3	Moderate accident	4/25 2100 to 4/27 1500	17.9 MCi	Upper air and surface	
N-4	See N-3	See N-3	See N-3	See N-3	fast mode
U-1	Isotopic release rate, 4.77E+04 Ci/hr	4/25 2100 to 5/6 2100	12.6 MCi	Upper air and surface	
U-2A	External Rad file	4/25 2100 to 5/6 2100	12.6 MCi	Upper air and surface	ATMES source term
U-2B	External Rad file	4/25 2100 to 5/6 2100	12.6 MCi	Upper air and surface	ATMES source term, 600 meter release height
U-3	Mix specified by analyst, 20% of core I-131 released	4/25 2100 to 5/6 2100	7.0 MCi	Upper air and surface	
U-4A	Percent Inventory, TDST, 20.0% of core I-131 released	4/25 2100 to 4/30 2100	12.6 MCi	Upper air and surface	ATMES source term grouped into five time periods
U-4B	Percent Inventory, TDST, 20.0% of core I-131 released	4/25 2100 to 4/30 2100	12.6 MCi	Upper air and surface	600 meter release height
U-5	See U-2A	See U-2A	See U-2A	Upper air Climatology	See U-2A
U-6	See U-2A	See U-2A	See U-2A	See U-2A	fast mode
U-7	See U-2A	See U-2A	See U-2A	See U2-A	Reduced spatial domain

The user-defined source terms were run using source term data from the Chornobyl literature. Since detailed source term data is usually not available until an accident has been thoroughly studied, the user-defined source term runs offered the opportunity to determine how well the software predicts the actual air concentration data.

The ATMES report provided the most detailed source term. It was used to calculate the release rate of I-131 for the U-1 and U-3 runs, prepare an external RAD file for the U-2 series of data runs, and define five releases for the U-4 series.

Data Used in Comparisons

As previously discussed, I-131 is the most important short-lived radionuclide to consider in the release from the Chornobyl accident since it, along with Cs-137, is responsible for most of the radiation exposure received by the general population. The Commission of the European Communities (CEC, also referred to as EC, European Community) maintains data collected from the accident at the Joint Research Center (JRC) in Ispra, Italy. Data collected for I-131 was published in the CEC Report EUR 12800 EN [Graziani, *et al*.]. This dataset was used in the ATMES study for comparison of the 21 model participants' results. Table 10 displays the measured air concentration values used in this research, and Figure 33 displays the location of the monitoring sites listed in Table 10. Chornobyl's location is identified with the ∇ symbol. (The concentration measurements in Table 10 display are unedited from the data provided by Lawrence Livermore National Laboratory [Foster, K].) Note from Figure 33 the absence of monitoring sites inside the former Soviet Union. Research efforts to obtain I-131 air concentration data inside the former Soviet Union were unsuccessful. HPAC predictions are compared to each point in the measured values to determine the factor the prediction is from the true value using the following equation:

$$Factor\_from\_Data = \frac{HPAC\_Measured\_Data}{Observed\_Data} \quad (2)$$

Table 10. Daily Iodine-131 Air Concentration Data

Location Name	Location (lat, long)	time of daily measurement (GMT)	1 May (Bq/m^3)	2 May (Bq/m^3)	3 May (Bq/m^3)	4 May (Bq/m^3)	5 May (Bq/m^3)
Paris, France	48.85 N 2.36 E	09:00	0.510000	1.929999	0.180000	0.008300	0.033000
Mol, Belgium	51.18 N 5.12 E	09:00	0.000100	1.680000	1.980000	0.810000	0.100000
Aachen, Germany	50.76 N 6.10 E	08:00	N/A	1.905000	2.257000	0.684000	0.074000
Monaco	44.73 N 7.42 E	09:00	0.150000	1.400000	2.900000	2.799999	1.299999
Ispra, Italy	45.80 N 8.36 E	12:00	13.910000	15.280000	8.790000	2.180000	0.750000
Berlin, Germany	52.50 N 13.42 E	12:00	0.850000	0.090000	0.215000	0.814000	0.533000
Hannover, Germany	52.38 N 9.73 E	09:00	0.001000	0.018000	0.389000	0.629000	0.444000
Stockholm, Sweden	59.33 N 18.08 E	~ 07:20 – ~ 08:30	0.073300	0.058500	0.041600	0.023400	0.091200
Bratislava, Czechoslovakia	48.16 N 17.16 E	05:00	14.400000	4.900000	1.000000	5.500000	1.200000
Budapest, Hungary	47.50 N 19.10 E	08:00	1.900000	4.100000	0.750000	1.600000	0.420000
Thessalonika, Greece	40.59 N 22.95 E	08:00	N/A	N/A	0.200000	1.400000	5.100000
Helsinki, Finland	60.13 N 25.00 E	~ 12:15 – ~ 16:50	0.660000	1.030000	0.790000	0.500000	0.310000

source: Foster, K.

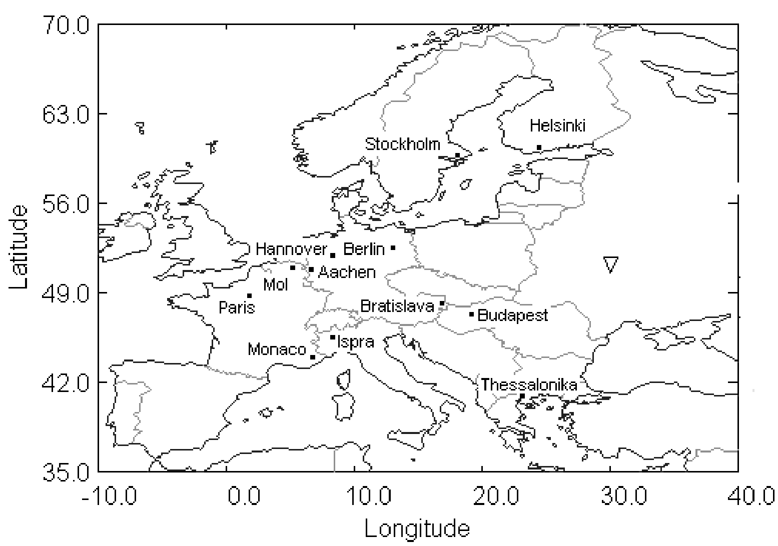

Figure 33. Location of Air Concentration Measurements

Results of NFAC Generated I-131 Source Terms

The NFAC-generated source term data runs served as a performance evaluation of the software as if the Chornobyl accident was ongoing and no detailed information about the source term was available. (If the source term were known the analyst would be best served using the user-generated source term specifications, which are discussed beginning on page 59.) For this set of runs the analyst is able to select from three available options: *Plant Conditions*, *Moderate* or *Severe* accident.

Plant Conditions Source Term

Using the *Plant Conditions* specification, the analyst is able to select the *Prompt Critical Power Excursion* option, representing how the Chornobyl accident occurred. Two runs were conducted using this option. The first used the default input parameters previously discussed (N-1A). A second test was run to determine the effects of increasing the power level (N-1B). Increasing the power level from 2775 MW(t) to 3200 MW(t) (the full-power rating of the reactor) would generate a larger core inventory, using the methodology discussed in Chapter III. Tables 11 and 12 display the results from data runs N-1A and N-1B, respectively.

Severe Accident Source Term

The *Severe* accident option is one of the two options available when the analyst selects the *Operational Mode* specification. It is characterized by a large release of activity over a short-duration time period. NFAC uses a built-in source term file named *acsrbmk* to define the *Severe* accident condition, which uses a reactor power level of 2775 MW(t). The default release period for the built-in *Severe* accident condition is 30 hours. The results for this run (N-2) are displayed in Table 13.

Table 11. I-131 Air Concentration for Plant Conditions at 2775 MW(t) (N-1A)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	5.47E-18	7E-16	4.28E-03	0.15
Mol	0.00E+00	0.00	0.00E+00	0.00	4.73E-08	2E-08	5.12E-02	0.06	1.41E+01	141
Aachen	0.00E+00	N/A	0.00E+00	0.00	9.81E-02	0.04	4.78E-01	0.70	4.12E+01	557
Monaco	0.00E+00	0.00	1.23E-09	9E-10	5.58E-02	0.02	6.92E-02	0.02	9.88E-02	0.08
Ispra	0.00E+00	0.00	2.55E-02	0.002	8.42E-01	0.10	1.54E+00	0.71	6.18E+00	8.24
Berlin	3.60E+00	4.24	6.38E+00	70.89	1.68E+02	781	4.03E+03	4950	2.42E+05	5E+05
Hannover	4.00E-09	4E-06	6.44E-16	4E-14	1.32E+00	3.39	7.42E+01	118	6.34E+02	1428
Stockholm	3.61E-02	0.49	3.61E-02	0.62	1.06E-01	2.55	7.37E+01	3150	2.04E+00	22.37
Bratislava	1.36E+02	9.44	4.04E+03	824	6.28E+04	6E+04	1.66E+05	3E+04	1.76E+06	2E+05
Budapest	1.21E+03	637	3.61E-02	0.01	3.40E+05	5E+05	9.11E+05	6E+05	8.54E+06	1E+07
Thessalonika	5.59E-03	N/A	1.83E+01	N/A	1.86E+03	9300	1.39E+04	9929	1.85E+05	4E+04
Helsinki	3.06E+01	46.36	3.06E+01	29.71	3.08E+01	38.99	3.24E+01	64.80	3.43E+01	111
Fraction that fall within a factor of 100 (F100)		0.40		0.36		0.50		0.42		0.30

Table 12. I-131 Air Concentration for Plant Conditions at 3200 MW(t) (N-1B)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	5.57E-18	7E-16	4.94E-03	0.15
Mol	0.00E+00	0.00	0.00E+00	0.00	1.67E-07	8E-08	5.89E-02	0.07	1.63E+01	161
Aachen	0.00E+00	N/A	0.00E+00	0.00	1.13E-01	0.05	5.51E-01	0.81	4.76E+01	643
Monaco	0.00E+00	0.00	1.00E-09	7E-10	6.43E-02	0.02	7.97E-02	0.03	1.41E-01	0.10
Ispra	0.00E+00	0.00	2.94E-01	0.02	9.71E-01	0.11	1.77E+00	0.81	1.45E-01	0.19
Berlin	4.16E+00	4.89	7.35E+00	81.67	1.93E+02	898	4.65E+03	5712	7.13+05	1E+06
Hannover	4.38E-09	4E-06	6.74E-16	4E-14	1.52E+00	3.91	8.55E+01	136	7.31E+02	1646
Stockholm	4.16E-02	0.57	4.16E-02	0.71	1.22E-01	2.93	8.50E+00	363	2.36E+00	25.88
Bratislava	1.57E+02	10.90	4.66E+03	951	5.96E+04	6E+04	1.68E+05	3E+04	2.03E+06	2E+06
Budapest	1.40E+03	737	4.37E+04	1E+04	6.48E+04	9E+04	1.05E+06	7E+05	9.85E+06	2E+07
Thessalonika	6.44E-03	N/A	2.11E+01	N/A	2.15E+03	1E+04	1.60E+04	1E+04	2.14E+05	4E+04
Helsinki	3.52E+01	53.33	3.52E+01	34.17	3.55E+01	44.94	3.77E+01	75.40	3.97E+01	128
Fraction that fall within a factor of 100 (F100)		0.40		0.36		0.50		0.42		0.30

Table 13. I-131 Air Concentration for Severe Accident (N-2)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	4.53E-13	3E-12	7.51E-11	9E-09	3.04E-03	0.09
Mol	0.00E+00	0.00	0.00E+00	0.00	3.53E-02	0.02	1.33E-01	0.16	6.32E+00	84.41
Aachen	0.00E+00	N/A	1.95E-16	2E-16	2.08E-01	0.01	4.06E-01	0.59	1.30E+01	177
Monaco	0.00E+00	0.00	1.18E-03	8E-04	2.45E-02	0.008	2.75E-02	0.01	3.07E-02	0.02
Ispra	2.30E-17	2E-17	1.69E-01	0.01	2.13E-01	0.02	2.65E-01	0.12	4.09E-01	0.55
Berlin	4.85E-01	0.57	9.72E-01	10.80	7.69E+01	358	1.10E+03	1351	1.18E+04	2E+04
Hannover	1.16E-08	1E-05	2.66E-04	0.01	1.26E+00	3.24	4.05E+01	64.39	1.24E+03	2793
Stockholm	1.18E-02	0.16	1.18E-02	0.20	1.28E-01	3.08	4.54E+00	194	1.51E+00	16.06
Bratislava	6.01E01	4.17	5.76E+02	118	3.68E+03	3680	8.06E+03	1465	1.85E+04	2E+04
Budapest	3.69E+02	194	3.56E+03	868	1.17E+04	2E+04	2.10E+04	1E+04	3.97E+04	9E+04
Thessalonika	1.06E-02	N/A	7.03E-01	N/A	8.84E+00	44.20	4.43E+01	31.64	1.54E+02	30.20
Helsinki	3.37E+00	5.11	3.38E+00	3.28	3.56E+00	4.51	3.74E+00	7.48	3.75E+00	12.10
Fraction that fall within a factor of 100 (F100)		0.40		0.45		0.58		0.58		0.58

Moderate Accident Source Term

The *Moderate* accident option is the other option available when the analyst selects the *Operational Mode* specification. It is characterized by a lesser release of activity over a longer period of time than the *Severe* accident option. NFAC uses a built-in source term file named *acmrbmk* to define the *Moderate* accident conditions, which uses a reactor power level of 2700 MW(t). The default release period for the *Moderate* accident condition is 42 hours. Table 14 displays the results for this run (N-3).

Results of User Defined I-131 Source Terms

User-defined source terms are available using the *Isotopic Release Rates*, *Percent Inventory*, *Mix Specified by Analyst*, and *External Rad File* specifications. These specifications should better model the Chornobyl accident than the NFAC-generated source terms, because they allow analyst control of the source term.

Table 14. I-131 Air Concentration for Moderate Accident (N-3)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.21E-18	4E-17
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	6.18E-07	6E-06
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	2.40E-04	0.003
Monaco	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	7.66E-17	3E-17	4.53E-13	3E-13
Ispra	0.00E+00	0.00	0.00E+00	0.00	2.12E-16	2E-17	4.74E-10	2E-10	1.24E-05	2E-05
Berlin	0.00E+00	0.00	0.00E+00	0.00	5.44E-10	3E-09	4.03E-04	5E-04	1.50E-01	0.28
Hannover	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	3.33E-09	5E-09	9.15E-03	0.02
Stockholm	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	3.10E-12	1E-10	2.92E-05	3E-04
Bratislava	3.85E-06	3E-07	2.60E-03	0.001	9.04E-02	0.09	4.08E-01	0.07	4.74E+00	3.95
Budapest	1.22E-03	0.001	1.25E-01	0.03	1.45E+00	1.93	4.58E+00	2.86	2.83E+01	67.38
Thessalonika	0.00E+00	N/A	6.55E-04	N/A	8.94E-02	0.45	1.17E+00	0.84	9.32E+00	1.83
Helsinki	0.00E+00	0.00	0.00E+00	0.00	5.00E-10	7E-10	4.61E-09	9E-09	2.20E-08	7E-08
Fraction that fall within a factor of 100 (F100)		0.00		0.09		0.25		0.25		0.42

Isotopic Release Rate Source Term

For this source term specification the analyst is able to specify an amount of activity to be released per unit time for each isotope contributing to the source term. The ATMES source term specifies a release of 12.6 MCi of I-131. For the eleven-day duration of the release, the linear release rate is then 4.77E+04 Ci/hr. Although the Chornobyl source term is known to not have been a constant, linear release (see Figure 5 on page 18), this specification is tested since this type of limited source term information may be what an analyst has available in the early stages of an accident. The results of this run (U-1) are displayed in Table 15.

External Rad File Source Term

A Rad file is created by NFAC after the analyst has defined the incident. It contains data for the activity released. The information in the file is passed to SCIPUFF for transport and dispersion. The analyst also has the capability to create a Rad file

Table 15. I-131 Air Concentration for Isotopic Release Rate (U-1)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.55E-19	2E-17	4.48E-05	0.001
Mol	0.00E+00	0.00	0.00E+00	0.00	9.51E-12	5E-12	4.02E-03	0.004	1.48E-01	1.48
Aachen	0.00E+00	N/A	0.00E+00	0.00	9.39E-03	0.004	4.88E-02	0.07	4.31E-01	5.82
Monaco	0.00E+00	0.00	7.19E-11	5E-11	5.81E-05	2E-05	7.22E-05	3E-05	1.03E-03	8E-04
Ispra	0.00E+00	0.00	2.67E-04	2E-05	1.23E-02	0.001	2.26E-02	0.01	6.46E-02	0.09
Berlin	3.77E-02	0.04	6.66E-02	0.74	1.75E+00	8.14	4.21E+01	51.72	4.85E+01	90.99
Hannover	3.91E-14	4E-11	1.54E-16	9E-15	1.38E-02	0.04	7.75E-01	1.23	6.62E+01	149
Stockholm	3.78E-03	0.05	3.78E-03	0.06	9.01E-03	0.22	7.70E-01	32.91	2.13E+00	23.36
Bratislava	1.42E+00	0.10	4.22E+01	8.61	5.40E+02	540	1.74E+02	31.64	2.59E+03	2158
Budapest	1.26E+01	6.63	3.96E-02	0.01	3.55E+03	4733	9.51E+03	5944	8.93E+04	2E+05
Thessalonika	3.47E-05	N/A	1.91E-01	N/A	1.95E+01	97.5	1.45E+02	104	1.94E+03	380
Helsinki	3.20E-01	0.48	3.20E-01	0.31	3.20E-01	0.41	3.43E-01	0.69	3.58E-01	1.15
Fraction that fall within a factor of 100 (F100)		0.50		0.45		0.42		0.58		0.50

outside of NFAC. The advantage is being able to provide SCIPUFF detailed information about the release. The ATMES source term provides the detail needed to take advantage of this specification. One of these detailed items is the height of release of the source term (see Table 3 on page 20). Most of the release periods give a release height of 300 meters. However, the release height for the first 24 hours is 600 meters. Since only a single release height can be given for an NFAC incident, two runs are conducted. Table 16 displays the U-2A results for the 300 meters release height, and Table 17 displays the U-2B results for the 600 meters release height.

Mix Specified by Analyst Source Term

This source term specification allows the analyst to provide a gross release rate of the activity and the percent of the total core inventory released in each of 12 categories of radionuclides. Using the ATMES source term as a reference, the total release of I-131 equates to a gross release rate of 7.4 Ci/sec. With 20% of the I-131 core inventory

Table 16. I-131 Air Concentration for External Rad File at 300m (U-2A)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	6.37E-14	2E-12
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	7.57E-10	9E-10	3.69E-03	0.05
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	1.94E-03	0.003	1.40E-03	0.02
Monaco	0.00E+00	0.00	6.01E-15	4E-15	1.28E-10	3E-05	2.20E-10	8E-11	3.60E-10	3E-10
Ispra	0.00E+00	0.00	8.15E-04	5E-05	1.44E-02	0.002	3.66E-02	0.02	1.11E-01	0.15
Berlin	8.60E-03	0.01	1.65E-03	0.02	2.15E-02	0.10	6.57E-01	0.81	1.44E+01	27.0
Hannover	0.00E+00	0.00	0.00E+00	0.00	1.38E-05	4E-05	4.66E-02	0.07	4.43E-01	1.00
Stockholm	9.05E-04	0.01	9.06E-04	0.02	1.82E-03	0.04	1.46E-03	0.06	6.41E-02	0.70
Bratislava	2.67E+00	0.20	9.70E+00	2.00	1.31E+01	13.10	5.31E+01	9.65	5.49E+01	45.75
Budapest	2.69E-01	0.14	9.78E+00	2.39	1.03E+01	13.70	4.14E+01	25.90	3.19E+02	760
Thessalonika	3.20E-09	N/A	3.68E-03	N/A	7.35E-01	3.68	8.26E+00	5.90	6.93E+01	13.59
Helsinki	8.10E-03	0.01	8.10E-03	0.008	8.12E-03	0.01	9.44E-03	0.02	1.02E-02	0.03
Fraction that fall within a factor of 100 (F100)		0.50		0.36		0.50		0.67		0.75

Table 17. I-131 Air Concentration for External Rad File at 600m (U-2B)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	9.88E-14	3E-12
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	8.25E-10	1E-09	7.91E-03	0.08
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	2.16E-03	0.003	2.85E-03	0.04
Monaco	0.00E+00	0.00	4.47E-14	3E+03	1.59E-10	6E-11	2.44E-10	9E-11	4.56E-10	4E-10
Ispra	0.00E+00	0.00	7.41E-04	5E-05	2.01E-02	0.002	4.27E-02	0.02	1.72E-01	0.23
Berlin	1.06E-02	0.01	2.01E-03	0.02	2.62E-02	0.12	8.21E-01	1.01	2.11E+01	39.6
Hannover	0.00E+00	0.00	0.00E+00	0.00	1.57E-02	0.04	5.70E-02	0.09	6.60E-01	1.49
Stockholm	3.20E-04	0.004	3.20E-04	0.005	4.20E-04	0.01	2.12E-03	0.09	1.18E-01	1.29
Bratislava	3.58E+00	0.25	1.64E+00	0.33	1.83E+01	18.30	6.73E+00	4.81	6.18E+01	51.50
Budapest	3.66E-01	0.19	1.50E+01	3.68	1.44E+02	192	1.73E-02	3.46	3.84E+02	914
Thessalonika	2.97E-08	N/A	6.49E-03	N/A	9.24E-01	4.62	1.04E+01	7.43	8.27E+01	16.21
Helsinki	1.54E-02	0.02	1.54E-02	0.01	1.55E-02	0.02	1.70E-02	0.03	1.84E-02	0.06
Fraction that fall within a factor of 100 (F100)		0.40		0.36		0.50		0.67		0.75

released (taken from the Chornobyl literature), the total release for this test was 7.0 MCi. The results of the U-3 data run are displayed in Table 18.

Table 18. I-131 Air Concentration for Mix Specified by Analyst (U-3)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	2.50E-03	0.08
Mol	0.00E+00	0.00	0.00E+00	0.00	6.92E-12	4E-12	2.45E-04	3E-04	8.24E-02	0.82
Aachen	0.00E+00	N/A	0.00E+00	0.00	5.25E-05	2E-05	2.73E-02	0.04	2.41E-01	3.26
Monaco	0.00E+00	0.00	5.60E-11	4E-11	3.26E-05	1E-05	4.04E-05	1E-05	5.76E-03	0.004
Ispra	0.00E+00	0.00	2.44E-02	0.002	4.92E-01	0.06	8.99E-01	0.41	3.61E-01	0.48
Berlin	2.10E-02	0.02	3.72E-02	0.41	9.79E-01	4.55	2.35E+01	28.87	2.71E+02	508
Hannover	2.88E-14	3E-11	1.28E-16	7E-15	1.03E-02	0.03	4.33E-01	0.69	3.70E+01	83.33
Stockholm	2.11E-03	0.03	2.11E-03	0.04	5.03E-03	0.12	4.30E-02	1.84	1.19E+00	13.05
Bratislava	1.12E+00	0.08	2.35E+01	4.80	3.02E+01	30.20	8.52E+02	155	1.03E+03	858
Budapest	7.06E+00	3.72	2.21E+02	53.90	1.98E+03	2640	5.31E+03	3319	4.98E+04	1E+05
Thessalonika	1.97E-05	N/A	1.07E-01	N/A	1.09E+01	54.50	8.10E+01	57.86	1.08E+02	21.18
Helsinki	1.78E-01	0.27	1.79E-01	0.17	1.79E-01	0.23	1.89E-01	0.38	2.00E-01	0.65
Fraction that fall within a factor of 100 (F100)		0.50		0.45		0.58		0.58		0.67

Percent Inventory Source Term

This source term specification allows the analyst to provide a source term that varies over time vice *Isotopic Release Rate* and *Mix Specified by Analyst* in which the analyst defines a single, continuous release for the duration of the release period. However, NFAC can only accept up to five time dependent source term (TDST) periods, limiting the degree of detail an analyst can specify within the source term. For these two runs, the eleven releases of the ATMES source term were group into five releases, which accounted for the total release of 12.6 MCi. As with the *External Rad File* specification runs, U-2A and U-2B, two runs using different release heights were conducted. The results of the U-4A run, with a release height of 300 meters, are given in Table 19. Table 20 provides the results of the U-4B run, with a release height of 600 meters.

Table 19. I-131 Air Concentration for Percent Inventory at 300m (U-4A)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.30E-03	0.04
Mol	0.00E+00	0.00	0.00E+00	0.00	3.94E-13	2E-12	1.98E-03	0.002	2.74E+00	27.40
Aachen	0.00E+00	N/A	0.00E+00	0.00	1.77E-06	9E-07	3.16E-02	0.05	8.30E+00	112
Monaco	0.00E+00	0.00	1.55E-10	1E-10	6.93E-09	3E-09	1.08E-08	4E-09	9.09E-02	0.07
Ispra	0.00E+00	0.00	2.01E-03	1E-04	8.49E-02	0.03	1.93E-01	0.09	3.07E+00	4.09
Berlin	3.26E-01	0.38	6.45E-01	7.17	1.32E+01	1.50	3.42E+02	0.05	2.05E+04	4E+04
Hannover	0.00E+00	0.00	0.00E+00	0.00	7.34E-02	0.34	5.44E+00	8.65	7.25E+02	1633
Stockholm	6.12E-03	0.08	6.12E-03	0.10	9.49E-03	0.02	7.19E-01	30.73	3.03E+01	332
Bratislava	2.10E+02	1.46	6.09E+02	124	6.67E+03	1E+04	1.77E+04	3218	1.15E+05	1E+05
Budapest	2.12E+02	112	5.99E+03	1460	3.80E+04	5E+04	9.26E+04	6E+04	4.24E+05	1E+06
Thessalonika	5.42E-03	N/A	6.76E+00	N/A	6.28E+02	3140	5.13E+03	3664	3.22E+04	6314
Helsinki	6.37E+00	9.65	6.37E+00	6.18	6.40E+00	8.10	6.66E+00	13.32	7.00E+00	22.58
Fraction that fall within a factor of 100 (F100)		0.40		0.27		0.42		0.50		0.42

Table 20. I-131 Air Concentration for Percent Inventory at 600m (U-4B)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.56E-19	2E-17	2.50E-10	8E-09
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	8.91E-04	0.001	2.26E+00	22.60
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	1.80E-03	0.002	7.08E+00	95.68
Monaco	0.00E+00	0.00	8.97E-11	6E-11	6.06E-09	2E-09	9.91E-09	4E-09	7.53E-02	0.06
Ispra	0.00E+00	0.00	8.18E-04	5E-05	6.84E-02	0.008	1.69E-01	0.08	3.08E+00	4.11
Berlin	2.09E-01	0.25	4.71E-01	5.23	9.61E+00	44.70	2.91E+02	357	2.11E+04	4E+04
Hannover	0.00E+00	0.00	0.00E+00	0.00	3.42E-02	0.09	3.65E+00	5.80	5.58E+02	1256
Stockholm	1.21E-02	0.17	1.21E-02	0.21	1.40E-02	0.34	5.92E-01	25.30	3.38E+01	371
Bratislava	1.89E+01	1.31	6.13E+02	125	7.50E+03	7500	1.93E+04	3509	1.21E+04	1E+04
Budapest	2.23E+02	118	6.78E+03	1654	4.66E+04	6E+04	1.10E+05	7E+04	4.77E+05	1E+06
Thessalonika	3.91E-03	N/A	8.45E+00	N/A	9.47E+02	4735	6.59E+03	4707	3.91E+04	7667
Helsinki	6.98E+00	10.58	6.98E+00	6.78	6.99E+00	8.85	7.22E+00	14.44	7.62E+00	2.46
Fraction that fall within a factor of 100 (F100)		0.40		0.27		0.33		0.33		0.42

Comparison of Climatological Data

Although this research focuses on a previous accident with known consequences, most users of HPAC will need to analyze incidents that are just beginning, or have not yet occurred. For such scenarios, detailed current or forecast weather data may not be readily available for the user. Using the U-2A source term, an NFAC test using only the upper air profile climatology data was performed. The run was labeled U-5 and the results are displayed in Table 21. The air concentration contour plot of I-131 on 5 May for the U-5 run is displayed in Figure 34.

Table 21. I-131 Air Concentration for April Upper Air Climatology (U-5)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	4.15E-13	1E-11
Mol	1.07E-06	0.01	1.07E-06	6E-07	1.07E-06	5E-07	1.46E-06	2E-06	7.15E-06	7E-05
Aachen	2.07E-06	N/A	2.07E-06	1E-06	2.07E-06	9E-07	2.79E-06	4E-06	1.16E-05	2E-04
Monaco	8.64E-15	6E-14	8.64E-15	6E-15	8.64E-15	3E-15	8.64E-15	3E-15	4.37E-08	3E-08
Ispra	4.63E-08	3E-09	4.63E-08	3E-09	4.77E-08	5E-09	4.78E-08	2E-08	8.64E-07	1E-06
Berlin	3.11E-01	0.37	3.36E-01	3.73	4.92E-01	2.29	5.14E-01	0.63	6.60E-01	1.24
Hannover	7.06E-04	0.71	7.46E-04	0.04	7.97E-04	0.002	1.36E-03	0.002	1.99E-03	0.004
Stockholm	1.58E+01	216	1.82E+01	311	1.84E+01	442	4.54E+01	1940	5.15E+01	565
Bratislava	2.73E-01	0.02	2.74E-01	0.06	3.31E-01	0.33	3.57E-01	0.06	4.40E-01	0.37
Budapest	5.14E-01	0.27	6.24E-01	0.15	6.86E-01	0.92	1.01E+00	0.63	1.03E+00	2.45
Thessalonika	7.46E-05	N/A	7.62E-05	N/A	8.03E-05	4E-04	8.53E-05	6E-05	9.35E-05	2E-05
Helsinki	8.06E+02	1220	9.75E+02	947	1.29E+03	1630	1.72E+03	3440	1.96E+03	6320
Fraction that fall within a factor of 100 (F100)		0.50		0.36		0.25		0.25		0.25

Comparison of Standard Mode versus Fast Mode

The analyst has the option of having SCIPUFF run in the standard mode or the computationally less-intensive fast mode. Although the HPAC manual states that the fast mode option is designed for scenarios involving a large number of nuclear weapons, the

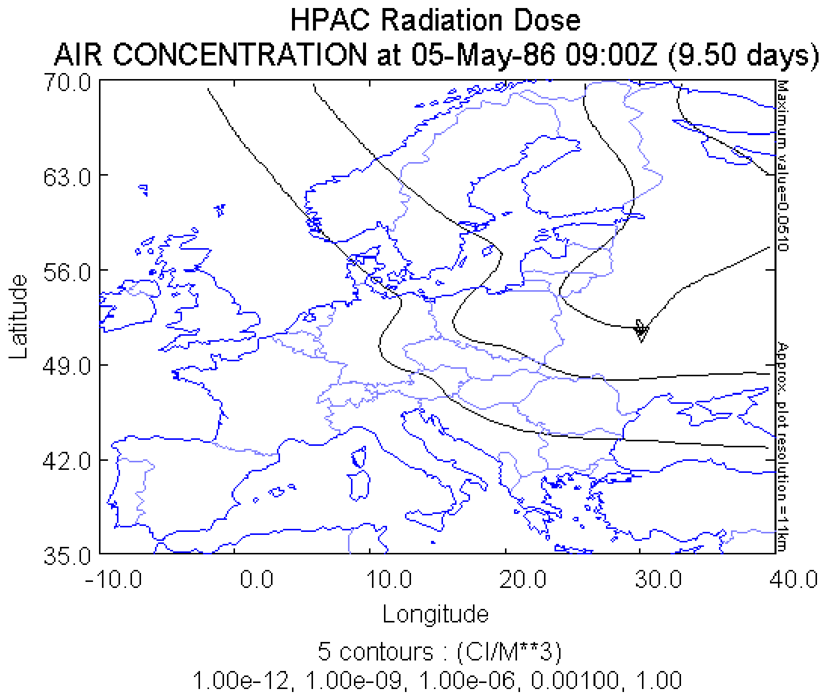

Figure 34. U-5 Hazard Plot of I-131 Air Concentration

option is available in all incident models. A previous research effort that studied the Three Mile Island accident found results obtained using the fast mode comparable to standard mode results [Frederick:62]. A comparison test is conducted to determine whether the standard mode versus fast mode outcome would be the same, given the larger spatial and temporal domain of this research. Two runs were conducted using the fast mode setting, using one of the worse performing runs (N-3) and one of the best performing runs (U-2A). The results of running the N-3 source term in fast mode is labeled as the N-4 run and are shown in Table 22 (Table 14 shows the results of the N-3 source term run in standard mode). The results of running the U-2A source term in fast mode is labeled as the U-6 run and are shown in Table 23 (Table 16 shows the results of the U-2A source term run in standard mode). The F100 values of the corresponding

standard mode runs are also displayed to allow for quick comparison. Finally, the air concentration contour plot of I-131 on 5 May for the U-2A run is displayed in Figure 35, and the corresponding U-6 fast mode run in Figure 36. A review of the *.err* files generated by HPAC shows that in fast mode SCIPUFF used 10-15% of the number of puffs as in the corresponding standard mode runs.

Table 22. I-131 Air Concentration for Moderate Accident in Fast Mode (N-4)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	8.91E-11	9E-10
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	2.71E-07	4E-06
Monaco	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	4.67E-08	4E-08
Ispra	0.00E+00	0.00	0.00E+00	0.00	8.65E-17	1E-17	5.92E-11	3E-11	1.10E-05	1E-05
Berlin	0.00E+00	0.00	0.00E+00	0.00	1.52E-7	7E-07	1.39E-04	2E-04	5.11E-02	0.10
Hannover	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.69E-09	3E-09	1.57E-04	4E-4
Stockholm	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	7.24E-10	3E-08	4.67E-05	5E-04
Bratislava	2.06E-04	1E-05	1.52E-03	3E-04	4.10E-02	0.04	1.88E-01	0.03	2.04E+00	1.70
Budapest	4.45E-04	2E-04	6.68E-02	0.02	8.37E-01	1.12	2.53E+00	1.58	1.44E+01	34.29
Thessalonika	0.00E+00	N/A	7.12E-04	N/A	9.03E-02	0.45	8.29E-01	0.59	5.59E+01	10.96
Helsinki	0.00E+00	0.00	0.00E+00	0.00	6.29E-10	8E-10	6.82E-09	1E-08	7.01E-06	2E-05
Fraction that fall within a factor of 100 (F100)		0.00		0.09		0.25		0.25		0.33
F100 values for N-3 source term (Standard Mode run)		0.00		0.09		0.25		0.25		0.42

Comparison of Results Using a Reduced Spatial Domain

The previous data runs used a spatial domain covering Europe. As will be pointed out in the results, a general observation of all the runs was that monitoring sites closer to Chornobyl provided better predictions than did the monitoring sites farther away. Using the U-2A data run as the input, a run was conducted changing the spatial domain from all of Europe to one that encompassed but did not extend much farther

Table 23. I-131 Air Concentration for Mix Specified by Analyst in Fast Mode (U-6)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Paris	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Mol	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	1.42E-09	1E-08
Aachen	0.00E+00	N/A	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	2.18E-05	3E-04
Monaco	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Ispra	0.00E+00	0.00	0.00E+00	0.00	4.98E-16	6E-17	0.00E+00	0.00	3.60E-17	5E-17
Berlin	9.80E-05	1E-04	9.80E-05	0.001	1.31E-04	6E-04	2.57E-01	0.32	3.96E+01	74.25
Hannover	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	2.06E-04	3E-04	1.26E+01	0.28
Stockholm	4.94E-05	7E-04	4.94E-05	8E-04	4.94E-05	0.001	2.05E-04	0.009	7.67E-02	0.84
Bratislava	9.47E-04	7E-05	3.05E-02	0.0006	1.27E+00	1.27	2.55E+01	4.64	3.28E+02	273
Budapest	2.33E-02	0.01	2.22E+00	0.54	2.22E+00	2.96	3.24E+02	2.03	2.52E+03	6000
Thessalonika	4.29E-08	N/A	3.01E-02	N/A	1.07E+00	5.35	1.39E+01	9.93	1.07E+02	20.98
Helsinki	3.31E-02	0.05	3.31E_02	0.03	3.31E-02	0.04	3.31E-02	0.07	3.40E-02	0.11
Fraction that fall within a factor of 100 (F100)		0.20		0.18		0.33		0.33		0.42
F100 values for U-2A source term (Standard Mode run)		0.50		0.36		0.50		0.67		0.75

beyond the three closest monitoring sites. The results of the reduced spatial domain data run are displayed in Table 24. The air concentration plot of the reduced spatial domain data run is displayed in Figure 37.

Table 24. Air Concentration for Reduced Domain (U-7)

City	1 May		2 May		3 May		4 May		5 May	
	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value (Bq/m^3)	Factor from Data	HPAC Value Bq/m^3)	Factor from Data
Stockholm	9.68E-04	0.01	9.68E-04	0.02	9.68E-04	0.02	9.78E-04	0.04	1.03E-03	0.01
Budapest	2.60E+00	1.37	3.49E+01	8.51	8.90E+01	119	1.35E+02	84.38	1.73E+02	412
Helsinki	5.92E-02	0.09	5.92E-02	0.06	5.92E-02	0.07	5.92E-02	0.12	5.92E-02	0.46
Fraction that fall within a factor of 100 (F100)		1.00		1.00		0.67		1.00		0.67
F100 values for U-2A source term of three closest monitoring sits		1.00		0.67		1.00		1.00		0.67

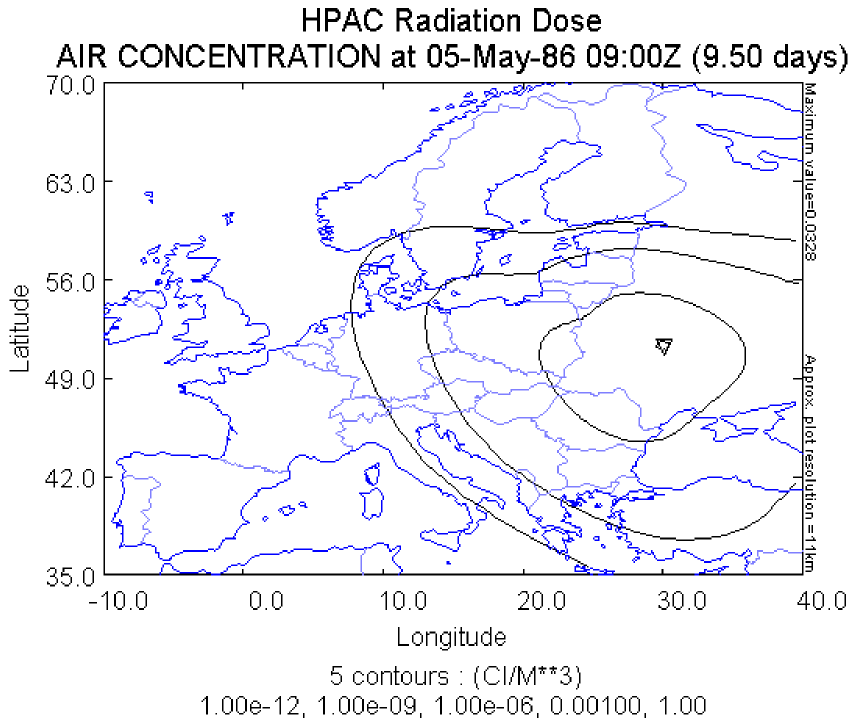

Figure 35. U-2A Hazard Plot of I-131 Air Concentration

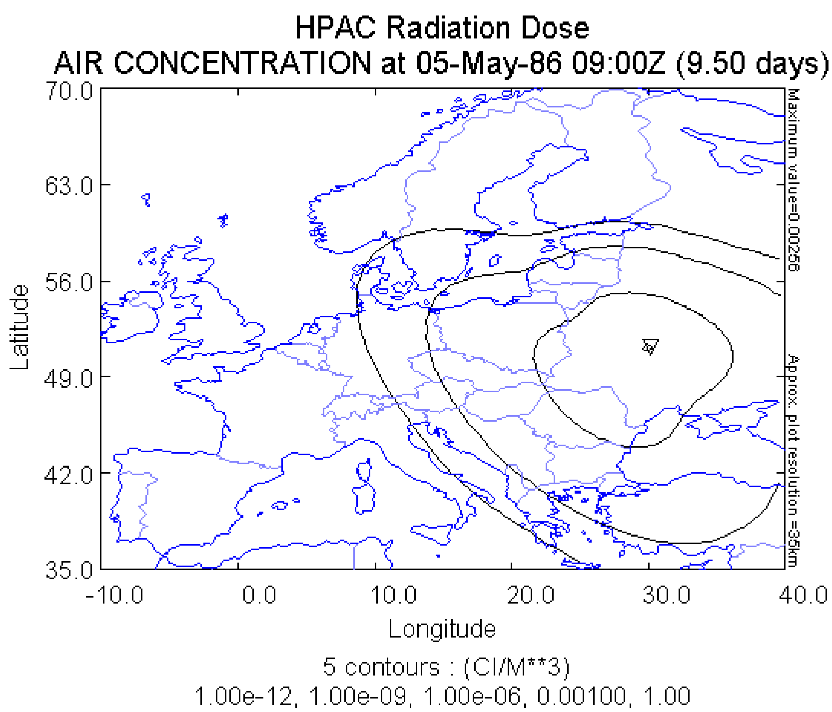

Figure 36. U-6 Hazard Plot of I-131 Air Concentration

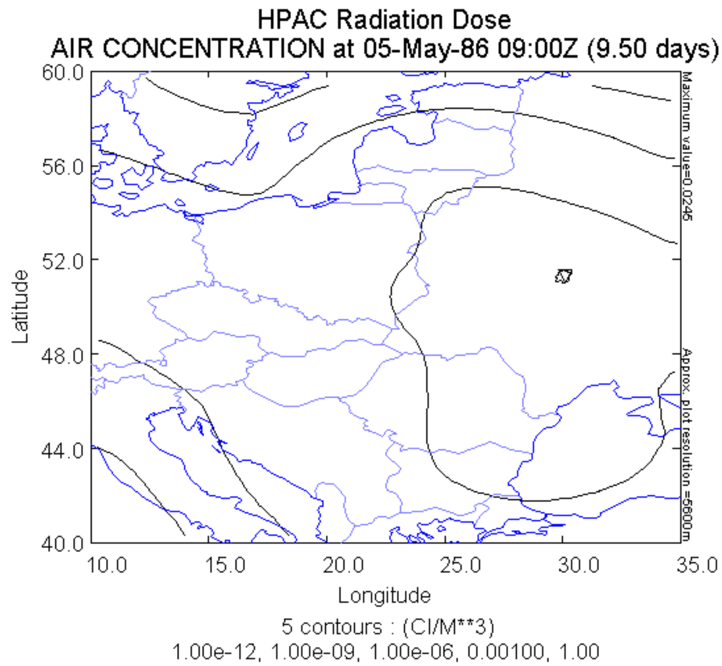

Figure 37. U-7 Hazard Plot of I-131 Air Concentration

Discussion of Results

A common feature of all the source term data runs is the significant number of underestimations by the HPAC software. Underestimations are typically unacceptable as they can provide a sense of relief, when in fact a danger exists. However, the opposite also is a problem, since large overestimations of the hazard will cause unnecessary panic and concern.

A general observation of all data runs is that the monitoring sites closest to Chornobyl (Stockholm, Budapest and Helsinki) had better predictions, with the majority of the HPAC predictions at these sites being within the accepted accuracy. Table 25 displays for each data run the percent of predictions that fall within a factor of 100 for all

sites, and the percent that falls within a factor of 100 for the three closest sites. Another general observation is that for the three farthest monitoring sites (Paris, Mol and Monaco) HPAC usually failed to predict the arrival of I-131 until after 1 May; once the software did predict the arrival at the three farthest monitoring sites only 4 of the 13 data runs showed predictions falling within a factor of 100 at least 50% of the time.

Table 25. Summary of F100 Values

Test ID	Source Term Specification	1 May	2 May	3 May	4 May	5 May	Average F100
N-1A	Plant conditions	0.40	0.36	0.50	0.42	0.33	0.40
N-1B	Plant conditions	0.40	0.36	0.50	0.42	0.33	0.40
N-2	Severe accident	0.40	0.45	0.58	0.58	0.58	0.52
N-3	Moderate accident	0.00	0.09	0.25	0.25	0.42	0.20
N-4	See-N-3	0.00	0.09	0.25	0.25	0.33	0.18
U-1	Isotopic release rate	0.50	0.45	0.42	0.58	0.50	0.49
U-2A	External Rad file	0.50	0.36	0.50	0.67	0.75	0.56
U-2B	External Rad file	0.40	0.36	0.50	0.67	0.75	0.54
U-3	Mix specified by analyst	0.50	0.45	0.58	0.58	0.67	0.56
U-4A	Percent inventory	0.40	0.27	0.42	0.50	0.42	0.40
U-4B	Percent inventory	0.40	0.27	0.33	0.33	0.42	0.35
U-5	See U-2A	0.50	0.36	0.25	0.25	0.25	0.32
U-6	See U-3	0.20	0.18	0.33	0.33	0.42	0.30
U-7	See U-2A (reduced domain)	1.00	1.00	0.67	1.00	0.67	0.87

Overall, the NFAC-generated source terms did not perform as well as the user-defined source terms. This was expected since the NFAC-generated source terms over-calculated the activity released. Reviewing the F100 values, the best performing NFAC-generated source term, the N-2 data run (*severe* accident plant condition), performed comparably to the worst performing user-defined source term, the U-1 data run (*isotopic release rate* specification).

Table 26. Fraction of Predictions that Fall Within a Factor of 100

Test ID	For All 12 Monitoring Sites	For the Three Closest Monitoring Sites
N-1A	0.40	0.60
N-1B	0.40	0.53
N-2	0.52	0.60
N-3	0.20	0.40
N-4	0.18	0.26
U-1	0.49	0.80
U-2A	0.56	0.87
U-2B	0.54	0.73
U-3	0.56	0.80
U-4A	0.40	0.60
U-4B	0.35	0.60
U-5	0.32	0.33
U-6	0.30	0.67
U-7	N/A	0.87

Another figure of merit for comparing the performance of each of the 14 data runs is the bias. It was computed using the following equation:

$$Bias = \tfrac{1}{N} \times \sum_i (C_i - O_i) \tag{3}$$

where

N = the total number of measurements for each data run (N=57 for all 12 monitoring sites, N=15 for the three closest monitoring sites)

C = the HPAC calculation value of the air concentration (Bq/m^3)
O = the measured observation value of the air concentration (Bq/m^3)
i = the iteration, from 1 to N, of the summation

The bias provides an indication of the average under prediction or over prediction of each data run. Unlike the factor from data value, which does not indicate the significance of a prediction of 0.00 Bq/m^3, the bias value does consider it in the calculation. Table 27 provides the results of calculating the bias for each of the data runs. A general

Table 27. Results of Bias Calculations

Test ID	For All 12 Monitoring Sites (Bq/m^3)	For the Three Closest Monitoring Sites (Bq/m^3)
N-1A	+214600	+652800
N-1B	+250200	+734000
N-2	+2133	+5089
N-3	-1.1	+1474
N-4	-0.6	+0.4
U-1	+1893	+6284
U-2A	+8.7	+24.6
U-2B	+11.2	+35.4
U-3	+150500	+571800
U-4A	+1226	+3240
U-4B	+1357	+3745
U-5	+3705	+10440
U-6	+705	+2350
U-7	N/A	+28.2

observation of the results of the bias calculations is that most of the data runs results of positive values for the bias, meaning the data run tended to over predict air concentration values. The magnitude of the bias provides an indication of the amount of over prediction or under prediction. A bias value of 0.0 Bq/m^3 would indicate that the data run, in total, neither under predicted or over predicted its results.

NFAC-generated Source Terms

The N-1 pair of source terms released three times the activity of I-131 specified in the Chornobyl literature that was used for the user-defined source terms. As a result, the majority of the predictions from these runs overestimated the air concentration measurements. (These over predictions are evident in the reviewing the values for the bias of the N-1A and N-1B data runs in Table 27.) Additionally, most of the underestimated predictions were values of 0.00E+00 Bq/m^3, meaning HPAC had yet to predict the arrival of the material at that location. The N-1A and N-1B data runs were identical, except the latter used a larger reactor power level. The result was a greater release and transport of I-131. 80% of the air concentration measurements from the N-1B data run were larger than from N-1A.

The N-2 and N-3 source terms also specified a release of I-131 greater than that specified in the literature, with the same result as in the N-1 series of runs. However, although the N-2 and N-3 runs released less total activity than the N-1 series, they are released over a significantly shorter duration. Whereas the N-1 series was released over an 11-day period, the N-2 source term was released in 30 hours, and the N-3 source term was released in 42 hours. This resulted in overestimations on or about the same order of magnitude as the N-1 runs if not greater. When reviewing the F100 values, the overall performance of the N-2 run was better than the N-1 and N-3 runs, indicating that a Chornobyl-type accident may best be modeled as a *Severe* accident when using NFAC-generated source terms. However, an examination of the bias values would indicate that the N3 data run is the best. This conclusion would be misleading, though since nearly

50% of the run's predictions are 0.00 Bq/m^3. Thus, the F100 and bias values must be reviewed together to gain an understanding of the performance of any data run.

The N-4 source term was identical to the N-3 source term except SCIPUFF was run in fast mode. A review of the F100 values displayed in Table 22 shows that overall the performance of the software was no worse in the fast mode, except for the 5 May F100 value. A review of the individual predictions, however, shows differences in the values of the non-zero predictions of an order of magnitude or more. These variations should be expected given the relaxation of the SCIPUFF-parameters discussed in Chapter III.

User-defined Source Terms

The U-1 source term took the total release from the ATMES source term and input it as a single release rate. Although the U-1 source term was a linear release it performed nearly as well as the detailed ATMES source term runs (U-2 A & B). The greatest difference from the U-2 pair occurred on 5 May. This most likely is the result of the linear release of this source term, since the true release decreased daily after the first day, and only began to increase during the middle period of the release timeline. The result is that on 5 May 92% of the U-1 values are greater than the values of the U-2A run (an identical run except for the source term).

An examination of the F100 values in Table 26 (page 72) shows that the U-2 pair of source terms performed the best. This was anticipated since they used the most detailed source term information. Reviewing the values that are within a factor of 100, both overestimated and underestimated values were generally less than a factor of 50 also. The results for the 600-meter release height from the U-2B run were often slightly

greater than the 300-meter release height from the U-2A run. A possible explanation has to do with the material being lofted higher in the atmosphere for transport. A review of the upper-air weather data showed that wind speed generally increased with altitude, as expected. The effect is that the I-131 moved down range more quickly, allowing for more activity to be deposited further away. With a short half-life of 8.02 days, the longer I-131 remained aloft, the less activity would eventually be deposited. For example, Paris is the monitoring site farthest from Chornobyl. HPAC predicted the arrival of material after 4 May for both runs, with the air concentration on 0900, 5 May from the U-2B run (600 meter release height) being greater than U-2A run (300 meter release height).

The U-3 source term was generated using the data in the RBMK reactor inventory file, releasing 20% of the total, as specified in the Chornobyl literature (see Table 2 on page 19). The resulting release of 13.0 MCi was similar to the ATMES release of 12.6 MCi. As with the U-1 run, the U-3 source term was a linear release and it performed nearly as well as the detailed U-2A run (an identical run except for the source term).

The performance of the U-4 series of source terms was nearly as good as the U-2 series. For example, the U-2A data run had an average F100 value of 0.56 and the U-4A data run had an average F100 value of 0.40. When observing the three closest monitoring sites the U-2A average F100 value was 0.87 and the U-4A average F100 value was 0.60. The reduction in performance was expected, given that the U-4 series involved compressing eleven daily release values, from the ATMES source term, into values for five release periods. A data run using the *Percent Inventory* specification with the first five daily release values of the ATMES source term was conducted, although not documented in this thesis. The performance for both the 300m and 600m releases was

better than the U-4A and U-4B data runs, although still slightly less than the U-2A and U-2B data runs. However, since these unreported data runs did not involve the release of the total source term this could affect have adversely affected the calculation of air concentrations later in the time period. Thus their performance could be suspect when compared to data runs using the total source term, and therefore were not reported.

The U-5 source term took the best performing user-defined source term, U-2A, and used the built-in upper air climatology to determine the effect on the predicted results of not having actual observations available. The results illustrate the importance of using the most current weather forecasts or actual observations. Not using the available weather data resulted in the U-5 run not performing as well as the U-2A run. As illustrated in Figure 34 (page 66) the HPAC climatology file resulted in the plume moving mainly to the north, with the highest concentrations being recorded at the Helsinki monitoring site. For the U-2A data run for which the U-5 used for a baseline, the highest concentrations were recorded to the west of Chornobyl at the Bratislava and Budapest monitoring sites, which generally agrees with the measured observations in Table 10 (page 55).

The U-6 source term was to test the performance of HPAC with SCIPUFF running in the fast mode. As with the standard versus fast mode runs using NFAC-generated source terms (N-3 and N-4), there was a difference in predicted values from the two runs, typically in the range of an order of magnitude. This is evident in reviewing the U-2A and U-6 hazard plots on page 69, where the same five contour values are not identically plotted. Although they generally have the same shape, the further out contours (contours with smaller values) show a larger displacement. In addition to the

reduced F100 values obtained when running in fast mode, there was a significant difference in the bias values also. The corresponding standard mode run (U-2A) had a bias calculation of +8.715 Bq/m^3, while the fast mode run increased over 8000% to +705 Bq/m^3. Thus, although a previous thesis pointed out that no significant difference was encountered when running the fast mode vice standard mode [Frederick:64], analysts should perform runs in both modes to determine the effect on the predictions.

The U-7 source term was identical to the U-2A source term. However, SCIPUFF calculations were done over a smaller domain to determine if a smaller domain improved the performance of HPAC. Because SCIPUFF is limited to the number of grid points generated over the 3D domain, specifying a smaller domain would improve the resolution, thus possibly resulting in improved performance. Comparing the results of the U-7 data run with the results of the corresponding monitoring sites of the U-2A data run shows that the reduced domain calculations resulted in F100 values as good as those of the full domain calculations, except for one day (2 May) when the F100 value is better. However, there was a downturn in performance for the bias of this reduced domain run. The bias value for the original U-2A data run (full domain of Europe) was +24.6 Bq/m^3 (the best bias value of any user-defined source term) for the three closest monitoring sites, whereas the bias value for the U-7 data run (reduced domain of U-2A run) was +28.2 Bq/m^3. Thus, although the reduced domain data run (U-7) resulted in the same number of predictions falling within a factor of 100, the actual value of the predictions were, on average, larger than their corresponding values in the U-2A data run.

Sensitivity Analysis of Input Parameters

A sensitivity analysis was attempted to determine the effect of changes in select input parameters on the resulting predictions. The impetus for such an analysis was to determine what changes, and how great the changes, in output would occur when a parameter is increased or decreased by 10% from a known baseline value. The baseline for this analysis was the U-4A data run. The two input parameters that were tested were the release height, and reactor power level, with a baseline of 300 m and 2775 MW(t), respectively. The reactor power level parameter is used to calculate the core inventory of radionuclides for the NFAC-generated source terms and the user-defined source terms that specify a percentage of the core inventory to release. Thus, increasing the reactor power would result in a greater source term. The height of release affects the transport because of the differing wind speeds and directions at varying altitudes. Figures 37, 38 and 39 display the output for changes in the release height, and Figures 40, 41 and 42 display the output for changes in the reactor power level.

The results of varying the release height (Figures 37, 38 and 39) show little variability in the general shape and location of the contours. The results of varying the reactor power (Figures 40, 41 and 42) shows even less difference in the shape and location of the contours. Thus, given the parameters of release height and reactor power level, variability in the release height value appears to have a greater impact on the output.

In addition to comparing contour plots for the sensitivity analysis, a comparison of results for one of the monitoring sites (Budapest) was performed. Those results showed extreme variability despite the relative agreement among the contour plots. For

example, 5 May air concentration values were 5.25E+03, 3.19E+02, 4.95E+03 for 330m, 300m, and 270m, respectively.

A final set of runs using the U-4A data run as a baseline was conducted to find out if a change in the source term would improve the performance. The impetus for these runs was to determine if the ATMES source term (12.6 MCi total release) could be improved upon by varying the release by ±10%. The results are summarized in Table 28. Whether the release was less than or greater than the ATMES source term resulted in reduced performance for each of the five days. The conclusion drawn from these results is that the ATMES source term is an accurate estimate of what was released based on the observed data. This is to be expected, given that the ATMES source term is the result of years of study by the IAEA, the Soviet Union, and others.

Comparison with ATMES Results

One of the purposes of the ATMES study was to "review and intercalibrate models of atmospheric transport of radionuclides over short and long distances" [Klug, *et al*:1]. Twenty-one models were evaluated in the study, including two from organizations in the United States: the Lawrence Livermore National Laboratory (LLNL) and Savannah River Laboratory (SRL). Although the full results of the evaluation were not available for this research, a brief comparison of the performance of the two U.S. models, as discussed in the ATMES text, with HPAC is made.

Both U.S models tended to underestimate the concentration values for I-131. The LLNL model underestimated 82% of its measurements, and the SRL model underestimated 78% of its measurements [Klug, *et al*.:70,168]. Similarly, using the U-2A data run, which used the ATMES source term, HPAC underestimated 73% of its

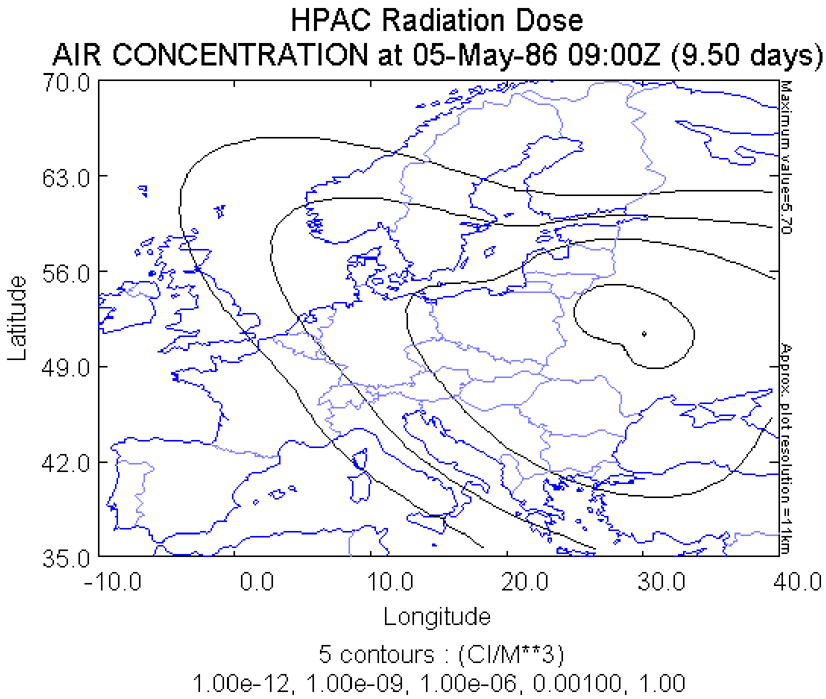

Figure 38. U-4A Hazard Plot for 330 m Release Height

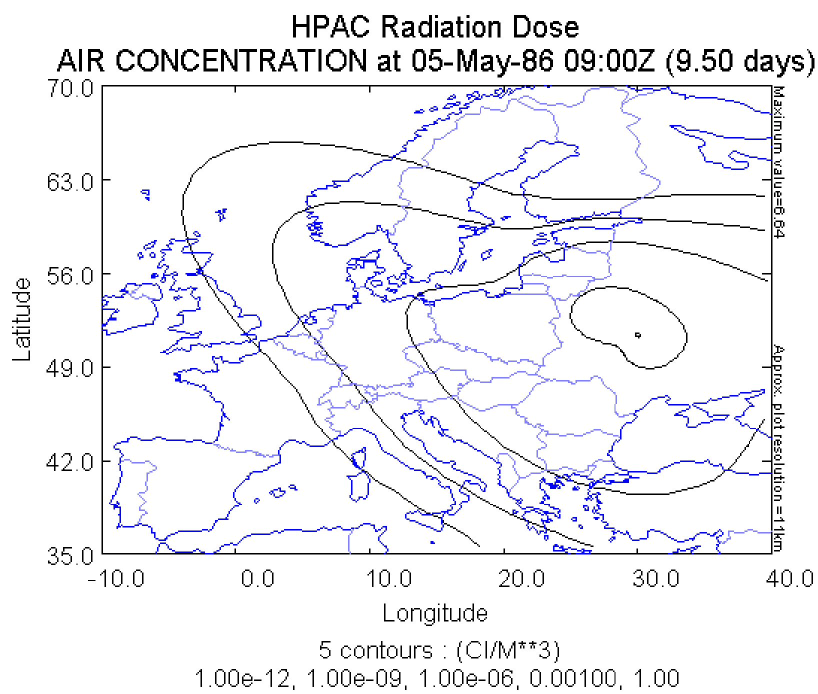

Figure 39. U-4A Hazard Plot for 300 m Release Height

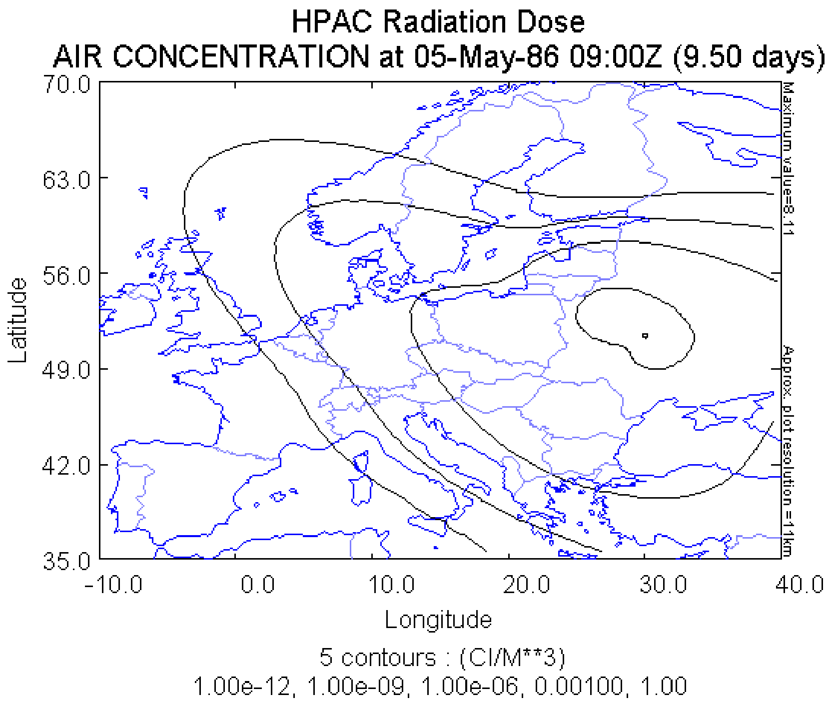

Figure 40. U-4A Hazard Plot for 270 m Release Height

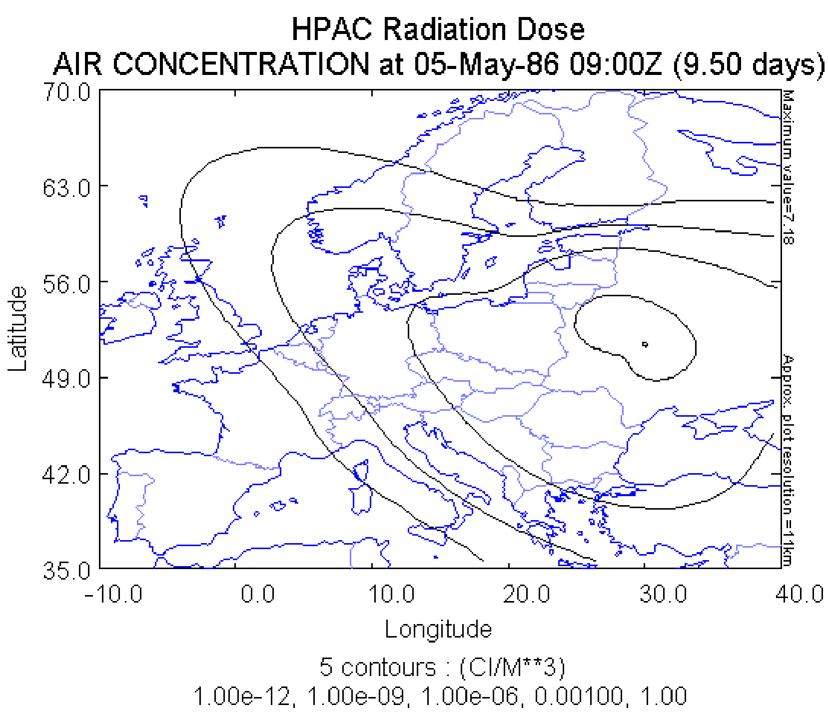

Figure 41. U-4A Hazard Plot for 3000 MW(t) Reactor Power

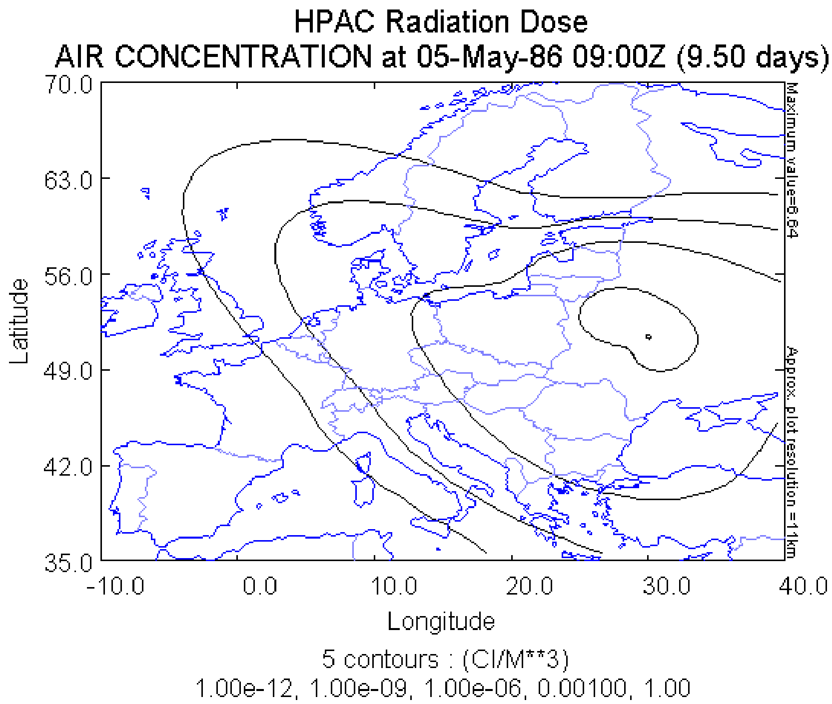

Figure 42. U-4A Hazard Plot for 2775 MW(t) Reactor Power

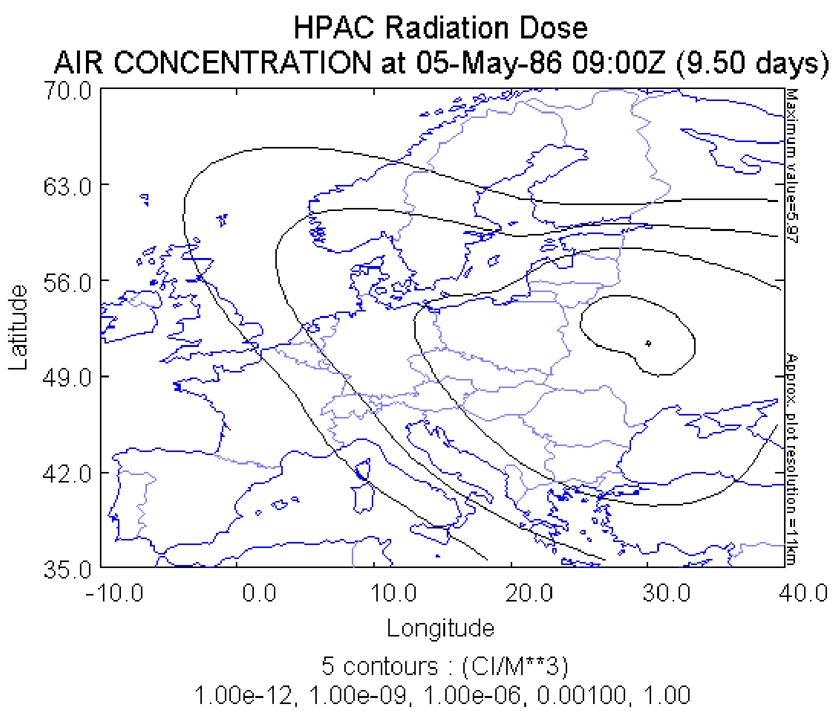

Figure 43. U-4A Hazard Plot for 2500 MW(t) Reactor Power

Table 28. Results of Estimating an Improved Source Term

Source Term	1 May	2 May	3 May	4 May	5 May
11.3 MCi	0.40	0.27	0.33	0.42	0.42
12.6 MCi	0.60	0.45	0.50	0.50	0.67
13.9 MCi	0.40	0.27	0.42	0.42	0.42

measurements. Another comparison is with the percent of predicted values that are within a factor of 5 of the observations. The LLNL model predicted 42% within a factor of 5, and the SRL model predicted 10% [Klug, *et al.*:70, 168]. HPAC predicted 12% of values within a factor of 5, which is between the predictions of the LLNL and SRL models.

V. Research Summary and Conclusions

This final chapter provides a summation of the research, and conclusions drawn from the research. Additionally, recommendations for further research using the HPAC software and notes for modifying the software are included.

Research Summary

This research has focused on using the NFAC incident module of the HPAC software to model an accident at a commercial nuclear power plant. Modeling the Chornobyl accident was important for at least two reasons. First, reactors of this design are still in operation, and given that human error was the proximate cause of the accident, a recurrence of the Chornobyl accident could take place. Secondly, the severity of the accident provides a significant data point for modeling the explosive release of large amounts of radioactive material. Overall, the results of the user-defined source terms agree better than do the NFAC-generated source terms with the best estimates of the source term as documented in the IAEA, ATMES, and Soviet reports.

Conclusions

Table 29 summarizes the average F100 values from each data run. In addition, an F100 value is calculated for each data run using the factor from data values of the three monitoring sites closest to Chornobyl (Budapest, Helsinki and Stockholm). Generally, the better the average F100 value of the data run, the better the average F100 value for the three closest monitoring sites. Thus the HPAC predictions of the closest monitoring sites contributed significantly to the overall performance of the particular data run, indicating there may be a spatial domain limit for the best performance of the HPAC

Table 29. Summary of Average F100 Values

Test ID	Average F100 of all Monitoring Sites	Average F100 of Three Closest Sites
N-1A	0.40	0.60
N-1B	0.40	0.53
N-2	0.52	0.60
N-3	0.20	0.40
N-4	0.18	0.26
U-1	0.49	0.80
U-2A	0.56	0.87
U-2B	0.54	0.73
U-3	0.56	0.80
U-4A	0.40	0.60
U-4B	0.35	0.60
U-5	0.32	0.33
U-6	0.30	0.67
U-7	N/A	0.87

software. For example, Frederick's study of the TMI-2 accident used a spatial domain with a radius on the order of 60 kilometers, and concluded that "the analyst should expect 94% of the predicted values to be within a factor of 100" [Frederick:70]. One of the software developers had predicted that HPAC might be "challenged" by the temporal and spatial domains of this problem [Sjoreen, 2001b].

In addition to a spatial domain limitation, another factor to consider in the overall performance of HPAC is the particulate nature of the Chornobyl release. This must be taken into account when the accident involves an explosion of the core. The NFAC source term model does not allow the analyst to define a particle size distribution to allow for settling out of larger particles closer to the source; and transport of smaller particles further away, before deposition. HPAC consistently underestimated predictions for the monitoring site farthest from Chornobyl for all data runs.

Given that regardless of which source term or source term specification was used the best results were obtained with the closer monitoring sites indicates that there is a limit to use of HPAC. Even, when the spatial domain is reduced, the improvement in performance for the three closest monitoring sites was not significant. HPAC is a "forward deployable, counterproliferation and counterforce tool for weapons of mass destruction (WMD)" [DTRA, 1999:2]. With this in mind, commanders are best served using the software on a tactical- or theater-level. Scenarios on a strategic-level may suffer from poor performance as distance away from the incident/accident increases.

Recommendations for Further Research

This research focused on one particular scenario for evaluating the NFAC module. The NFAC module is also able to model accidents at reprocessing facilities and research reactors. Those scenarios should be explored using known accidents. The September 1957 explosion at a nuclear fuel reprocessing (plutonium separation) plant in Kyshtym, USSR, and the October 1957 Windscale accident in England are examples.

Two of the other source term models in the HPAC software are also of concern to nuclear engineers. The nuclear weapon explosion (NWPN) and Radiological Weapon Incident (RWPN) modules warrant consideration for thesis research.

Finally, the source term data used for this research can be considered at best only an estimate. This is due to the severity of the Chornobyl accident and the lack of any ability to precisely monitor the release. Thus, it has been difficult to attribute errors in the research; were errors attributable to the source term estimate, the weather data, or the transport and diffusion model? To eliminate source term as a possible source of error, a study could look at tracer experiments that have been done in North America and Europe.

The European Tracer Experiment (ETEX), conducted in October and November 1994 is well documented. This would serve as a validation study of the SCIPUFF transport and dispersion model.

Notes on Modifying the HPAC Software

The research was conducted using HPAC version 3.2.1. During the research HPAC version 4.0 was released. However, it was not used for the research, based on the recommendation of Ms. Andrea Sjoreen of ORNL, because of computational errors by the NFAC incident model that resulted from migrating the software to a client/server architecture and rewriting the user interface in JAVA. Later during the research, ORNL made available a beta version of 4.0.1. However, even though it fixed the NFAC errors in HPAC version 4.0, many of the source term specifications in HPAC version 3.2.1 were not available in the 4.0.1 beta version. Thus, its use in this research would not have been as beneficial as using HPAC version 3.2.1. According to Ms. Sjoreen, when released, HPAC version 4.0.1 will have the same functionality as HPAC version 3.2.1. After working for a short time with the 4.0.1 beta version, the following comments are provided for improving future releases of the software.

1. In HPAC version 3.2.1 the spatial domain selected by the user was the default domain plotted following the SCIPUFF run. With HPAC version 4.0.1 beta there is no default plotted domain, even though the user specifies the spatial domain as part of the incident. There is currently no option to type the spatial domain coordinates into a dialog box to get a specific plot domain. Instead, the user takes the cursor and outlines a box around the incident in order to zoom into the domain. It is not easy to outline the same size box around different data runs. This makes comparing plots difficult, since the map

image may not always be the same for different runs, even when the same spatial domain is specified.

2. Both HPAC version 3.2.1 and the newer releases have the capability to build an output table (.tab file) that stores a given dose or dose rate at a specific geographic location. HPAC version 3.2.1 also has the capability to display the value at a specific location on the screen, eliminating the need to save the .tab file and then open it in a text editor to review. That useful feature is not available in HPAC version 4.0.1 beta.

3. The HPAC version 3.2.1 software contained three separate versions: *Operational*, *Extended* and *Ultimate*. The analyst needed to determine which version was appropriate for the particular scenario and select it from the START-HPAC menu in Windows. If the analyst wanted to use a different version, they would have to exit the current version and select another version. In HPAC versions 4.0 and 4.0.1 beta, there is only one file to select, and within the HPAC software the analyst selects the version to run. This allows for re-running of scenarios using the different versions without exiting the software. However, selecting the version to run from the *Edit* menu is confusing. The default is to run the scenario in the operational version. If the user selects to run the scenario in one of the other two versions it is a simple task to switch the version. However, if in reviewing the scenario before beginning the run the analyst chooses to review the version, the default version is highlighted in the dialog box, regardless of what version was selected previously.

4. An important input parameter for defining the release of material is the height of release. Both HPAC versions 3.2.1 and 4.0.1 beta allow for only a single release height to be specified for an incident. As the Chornobyl accident demonstrated, this is an

unlikely scenario for an explosive release. An option to specify the release height for each material release period would allow the software to more realistically simulate an incident.

Glossary

AFCCC – Air Force Combat Climatology Center

ATMES – Atmospheric Transport Model Evaluation Study

BWR – Boiling Water Reactor

Bq – Becquerel, unit of radioactive decay equivalent to 1 disintegration per second

Ci – Curie, unit of radioactive decay equivalent to 3.7E+10 disintegrations per second

CEC – Commission of the European Communities

DNA – Defense Nuclear Agency

DTRA – Defense Threat Reduction Agency

HASCAL – Hazard Assessment System for Consequence Analysis software

HPAC – Hazard Prediction and Assessment Capability software

JRC – Joint Research Center, located at Ispra, Italy

LLNL – Lawrence Livermore National Laboratory

NFAC – Nuclear Facility incident model, also known as a source term model

NPP – Nuclear Power Plant

NRC – Nuclear Regulatory Commission

ORNL – Oak Ridge National Laboratory

RASCAL – Radiological Assessment System for Consequence Analysis software

RBMK – *Reactor Bolshoi Moschnosti Kanalynyi*, Russian for Channelized Large Power Reactor

SCIPUFF – Second-order Closure Integrated PUFF atmospheric transport and diffusion model

SRL – Savannah River Laboratory

TADMOD – Transport And Dispersion MODel

Appendix A. Preparation of Custom Rad File Using ATMES Source Term

This appendix provides information on the Rad file that was prepared in order to run the HPAC software with a user-defined, custom source term. Most users of the HPAC software will typically specify conditions for the incident using NFAC, which computes the source term and prepares the resulting Rad file. Source terms can also be created outside NFAC and imported using the *External Rad File* option. For this research, a Rad file was prepared to mirror the specific releases of I-131 from the ATMES source term.

The Rad file defines the materials, computed doses, and plotted doses in an NFAC incident. When creating a custom Rad file, the burden is on the user to ensure the file is properly formatted and the data values represented are reasonable. SCIPUFF will not be able to process an incorrectly formatted Rad file. The Rad file is divided into 5 sections: material data, computed dose factors, plotted dose data, dose factors and non-SCIPUFF data. Each section is described below.

Material Data

Materials are substances transported by SCIPUFF. SCIPUFF recognizes two types of NFAC materials – depositing gas and non-depositing gas. Thus all materials released from a reactor are treated as a gas, with particles being treated as depositing gases 1 micron in diameter. This design decision is based on the indeterminate nature of the release from a reactor accident [Sjoreen, 2001b]. The first item in the material file is the Material Units, either Ci (Curies) or Bq (Becquerels). This is followed by the exposure duration, the total time from the start of the incident that SCIPUFF will transport and decay the material. Then the materials are described with their name,

number of particle size groups, mean particle size, and the release start time and release duration. The particles sizes defined in the Rad file are only used to help document the file. Each material file contains the particle size that is used in SCIPUFF (SCIPUFF assumes a mean particle size of 1 micron for all materials). Here is an example of the material data section of a Rad file involving five material releases:

```
BEGIN_SCIPUFF_DATA

MATERIAL_UNITS= Bq

EXPOSURE_DURATION= 11.00E+00 D

NUMBER_MATERIALS_AIR= 5
MATERIAL= BqDP1 1
1.0
RELEASE_START= 0.00000E-01 D
RELEASE_DURATION= 2.00000E+00 D
MATERIAL= BqDP2 1
1.0
RELEASE_START= 2.00000E+00 D
RELEASE_DURATION= 2.00000E+00 D
MATERIAL= BqDP3 1
1.0
RELEASE_START= 4.00000E+00 D
RELEASE_DURATION= 2.00000E+00 D
MATERIAL= BqDP4 1
1.0
RELEASE_START= 6.00000E+00 D
RELEASE_DURATION= 2.00000E+00 D
MATERIAL= BqDP5 1
1.0
RELEASE_START= 8.00000E+00 D
RELEASE_DURATION= 3.00000E+00 D

NUMBER_MATERIALS_GROUND= 0
```

Computed Dose Factors

Computed dose factors are the scaling factors that SCIPUFF uses to compute doses. In this section the user indicates how SCIPUFF will use the dose factors to compute doses. Each line includes the dose factor name, its dose units, and one of three identifiers for the type of activity to which the dose applies (AIR, GROUND, or SHINE). For this research, SCIPUFF calculated air concentration measurements of I-131. Here is an example of the computed dose factors section of a Rad file:

```
NUMBER_DOSE_FACTORS= 1
DOSE_FACTOR= AIR_CONCENTRATION Bq/M**3 AIR
```

Plotted Dose Data

Plotted doses are those quantities that are presented as the output from SCIPUFF. They consist of one or more computed doses in a linear combination defined in the above computed dose factors section. Each plotted dose is entered as its name, units and the number of component doses. A plotted dose often has the same name as a computed dose factor. It is the names of the plotted dose data that appear as the options available for plotting in the HPAC *Plot Control* window. Here is an example of the plotted dose data section of a Rad file:

```
NUMBER_PLOTTED_DOSES= 1
PLOTTED_DOSE_NAME= AIR CONCENTRATION
PLOTTED_DOSE_UNITS= Bq/m**3
NUMBER_COMPONENT_DOSES= 1
COMPONENT_NAMES= AIR_CONCENTRATION 1.0
```

Dose Factors

The dose factors are enclosed in the keywords "Begin_Dose_Factors" and "End_Dose_Factors". The data for each exposure time begin with the keyword "Exposure_Time" followed by those dose factors at that exposure time. Dose factors are entered in the order in which they are listed in the plotted dose data section above, with data for each plotted dose name beginning on a new line. The dose factors represent the activity of the material in the material unit defined at the start of the Rad file; in this case Becquerels. For each of the file materials, the dose factors indicate the activity of the material for the exposure time. Since SCIPUFF does not know what specific radioisotope it is transporting, only the total activity, the user must decay the material for each release time. In this case, I-131 with a half-life of 8.02 days, will show significant decay for each successive material release. For calculations at times other than those specified in the Rad file, SCIPUFF, by design, performs a linear (not exponential) decay of released materials. Here is an example of the dose factors section of a Rad file:

```
BEGIN_DOSE_FACTORS
EXPOSURE_TIME= 0.00000E+00 D
  2.46E+17   0.00E-1     0.00E-1     0.00E-1     0.00E-1
EXPOSURE_TIME= 2.00000E+00 D
  2.07E+17   6.92E+16   0.00E-1     0.00E-1     0.00E-1
EXPOSURE_TIME= 4.00000E+00 D
  1.74E+17   5.82E+16   2.08E+16   0.00E-1     0.00E-1
EXPOSURE_TIME= 6.00000E+00 D
  1.46E+17   4.90E+16   1.75E+16   5.82E+16   0.00E-1
EXPOSURE_TIME= 8.00000E+00 D
  1.23E+17   4.12E+16   1.47E+16   4.90E+16   7.19E+16
```

END_DOSE_FACTORS
END_SCIPUFF_DATA

Non-SCIPUFF Data

Since other programs besides SCIPUFF may use the RAD file, there are keywords defined to delimit data to be read by SCIPUFF and not read by SCIPUFF. All SCIPUFF data must appear between the keywords "Begin_SCIPUFF_Data" and "End_SCIPUFF_Data." Any non-SCIPUFF data should be placed at the end of the Rad file, and must be placed between the keywords "Begin_Special_Application_RAD_File_Data" and "End_Special_Application_RAD_File_Data". No non-SCIPUFF data appeared in the custom Rad files for this research, thus those keywords were excluded.

Appendix B. Weather Data

Since this research studied a past event it was possible to obtain the actual observed weather data. This contrasts with using numerical weather prediction (NWP) data, fixed winds, or HPAC's historical weather when performing a study of a scenario that has yet to occur. This appendix highlights the weather data used in this research.

The Air Force Combat Climatology Center (AFCCC) in Asheville, North Carolina provided the weather data upon submission of a Support Assistance Request (SAR) form found on the AFCCC public access website. Turn-around time for the request was one week. Coordination was made with AFCCC to provide the data in a format as close as possible to that used in HPAC [Foster, S.]. The data was received as Microsoft Excel spreadsheets, and, following additional formatting of the data and error checking, was saved as tab-delimited ASCII text files. The text files contained more than 24 Megabytes (Mb) of data covering the continent of Europe during the 11-day period of the accident and subsequent release.

HPAC recognizes several different formats for weather files. The format used in this research was *Observation*. The *Observation* file format has two subformats: *Profile* and *Surface*. *Profile* data consists of upper-air profile observations, and has a .prf extension. *Surface* data consists of surface (ground level) observations and has an .sfc extension. It was not uncommon for the upper-air profile observations to also contain observations made at or near ground level.

A typical upper-air profile input data file is shown in Figure 44. The first line for each profile contains the header data; information specific to the station providing the data. The first column in the header data contains the text "ID:" which HPAC uses to

recognize a new station and data. The second column contains the station ID, typically a numeric code assigned by the World Meteorological Organization (WMO). The third column contains the date the data was collected, and the fourth column contains the time. The fifth and sixth columns contain the location of the station expressed in decimal degrees of latitude and longitude, respectively. The last column in the header data contains the elevation above mean sea level (MSL) of the station. The rows that follow the header line contain the following information in six columns: the elevation at which the data was collected in units of meters, the wind speed in meters per second, the wind direction in degrees, the atmospheric pressure in millibars, the temperature in degrees Celsius, and the humidity as a percent. A typical range over which soundings were made was from 0 to 30,000 meters above ground level (AGL). Data were collected four times each day at 06:00, 12:00, 18:00 and 24:00 GMT. Entries of "-9999" denote missing or unmeasured data points. This is the value recognized by HPAC. However the standard

ID:	076450	860427	12.00	43.86	4.40	62
0	350	6	1002	16	41	
18	350	6	1000	15	38	
1358	345	10	850	02	69	
2892	355	8	700	-08	67	
5428	335	4	500	-25	39	
7008	235	6	400	-37	31	
8938	155	10	300	-53	-9999	
9314	155	10	283	-9999	-9999	
10118	170	8	250	-50	-9999	
11578	220	7	200	-49	-9999	
13468	210	7	150	-48	-9999	
16108	225	6	100	-52	-9999	
17947	180	2	75	-9999	-9999	
18420	180	6	70	-52	-9999	
20588	95	4	50	-55	- 9999	

Figure 44. Sample of Upper Air Profile Weather Data

meteorological practice is to identify missing data as “9999”. The Upper Air Profile data file used in this research was 4.23 Mb in size, and spanned the time period 18:00 GMT 25 April 1986 to 12:00 GMT 7 May 1986.

A typical surface observation input data file is shown in Figure 45. Each line of data contains the following information: station ID, date of the observation, time the data was collected, latitude of the station in decimal degrees, longitude of the station in decimal degrees, elevation of the station above MSL in units of meters, elevation above the ground at which the sounding was taken in meters, wind direction in degrees, wind speed in meters per second, atmospheric pressure in millibars, temperature in degrees Celsius and humidity in percent. Since weather measurements are typically never taken exactly at ground level (i.e. zero meters AGL), HPAC does not recognize non-positive numbers in the elevation column. An additional column was added to the data provided by AFCCC, with a value of “2” placed in for all the data points, to specify the elevation at which the sounding was taken. Values of “-9999” denote missing or unmeasured data points. Unlike the times at which upper-air data was collected, surface observations were taken at varying times throughout the day. The surface observation data file used in this research was 20.2 Mb in size and spanned the time period 21:00 GMT, 25 April 1986 to 03:00 GMT, 7 May 1986.

164340	860429	14.17	37.717	13.433	1035	2	260	1.5	-9999	-9999	-9999
164500	860429	14.17	37.567	14.283	965	2	220	3.6	-9999	-9999	-9999
164530	860429	14.17	37.083	14.217	33	2	230	7.2	-9999	-9999	-9999
164800	860429	14.17	36.683	15.133	51	2	260	6.7	-9999	-9999	-9999
165970	860429	14.17	35.850	14.483	91	2	240	5.1	999.2	16.0	72
166220	860429	14.17	40.517	22.967	4	2	180	4.1	1002.5	24.0	47
166410	860429	14.17	39.617	19.917	4	2	000	0.0	1006.5	18.0	59
166820	860429	14.17	37.917	21.300	12	2	290	5.1	1006.6	18.0	56
167160	860429	14.17	37.900	23.733	15	2	240	3.6	1002.2	21.0	53
167180	860429	14.17	38.067	23.550	31	2	210	5.1	1001.3	25.0	26
604190	860429	14.17	36.283	6.617	694	2	280	4.1	934.1	9.0	87
607150	860429	14.17	36.833	10.233	4	2	270	9.8	1009.6	15.0	72
064560	860429	14.18	50.233	4.650	299	2	350	4.6	-9999	-9999	-9999
109210	860429	14.18	47.983	8.900	794	2	-9999	0.5	-9999	-9999	-9999
107550	860429	14.19	49.317	10.633	467	2	010	2.1	-9999	-9999	-9999
010100	860429	14.20	69.300	16.150	14	2	030	8.8	1019.2	4.0	81
010250	860429	14.20	69.683	18.917	10	2	010	5.1	1020.7	4.0	58
011520	860429	14.20	67.267	14.367	13	2	100	6.7	1017.3	10.0	46
012410	860429	14.20	63.700	9.600	7	2	110	4.1	1015.0	12.0	29
012710	860429	14.20	63.467	10.933	17	2	250	3.6	1013.8	13.0	67
013110	860429	14.20	60.300	5.217	50	2	190	4.1	1010.8	6.0	100
013840	860429	14.20	60.200	11.083	204	2	160	4.1	992.5	8.0	66
014150	860429	14.20	58.883	5.633	9	2	180	5.1	1016.8	8.0	87
014520	860429	14.20	58.200	8.083	17	2	210	4.1	1016.9	6.0	81
014880	860429	14.20	59.900	10.617	17	2	100	1.5	1015.9	10.0	66
014940	860429	14.20	59.383	10.783	53	2	210	4.1	1011.5	10.0	76
024600	860429	14.20	59.650	17.950	61	2	310	2.1	1008.5	12.0	71
024640	860429	14.20	59.350	17.950	11	2	260	3.6	1015.5	11.0	76
025260	860429	14.20	57.667	12.300	169	2	310	1.0	997.7	11.0	62
025710	860429	14.20	58.583	16.250	8	2	260	5.1	1014.8	17.0	48
025900	860429	14.20	57.667	18.350	47	2	350	3.1	1011.2	12.0	82
026360	860429	14.20	55.550	13.367	106	2	310	6.7	1005.2	13.0	77
030030	860429	14.20	59.883	-1.300	5	2	200	4.1	1012.2	10.0	57
030170	860429	14.20	58.950	-2.900	21	2	160	7.2	1009.3	-9999	-9999
030750	860429	14.20	58.450	-3.083	39	2	160	6.2	1006.0	9.0	49
033180	860429	14.20	53.767	-3.033	10	2	250	5.7	1018.7	10.0	-9999
036830	860429	14.20	51.883	0.233	106	2	310	4.1	1008.2	12.0	50
037661	860429	14.20	51.283	0.033	-9999	2	270	4.1	-9999	12.0	40
037720	860429	14.20	51.483	-0.450	24	2	240	3.6	1018.0	14.0	41
037760	860429	14.20	51.150	-0.183	62	2	320	5.1	1013.4	13.0	41

Figure 45. Sample of Surface Observation Weather Data

Appendix C. HPAC Contour Plots

This Appendix contains HPAC contour plots. Each contour plot of I-131 air concentration is from 5 May 1986 (0900Z) near the end of the time period that the HPAC simulations were run. Thus, the plots capture a large extent of the movement of the material.

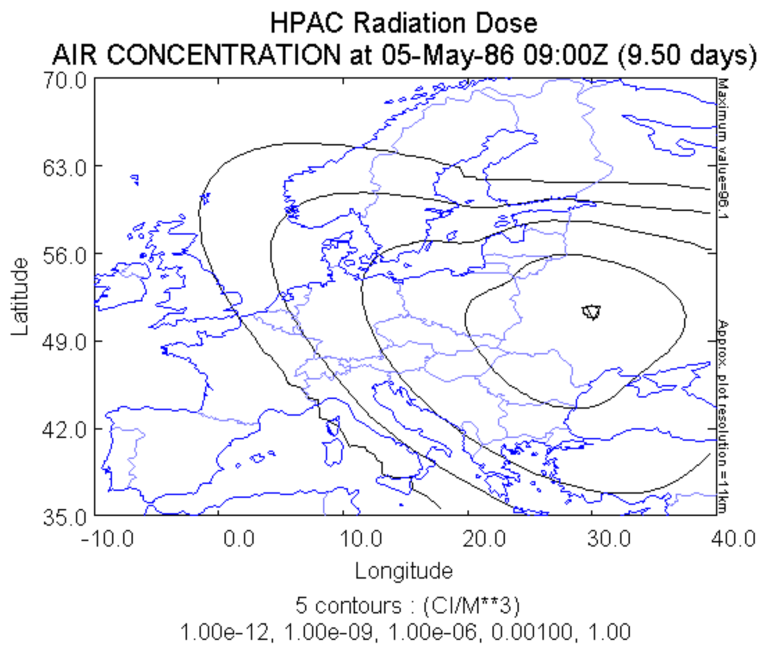

Figure 46. N-1A Hazard Plot of I-131 Air Concentration

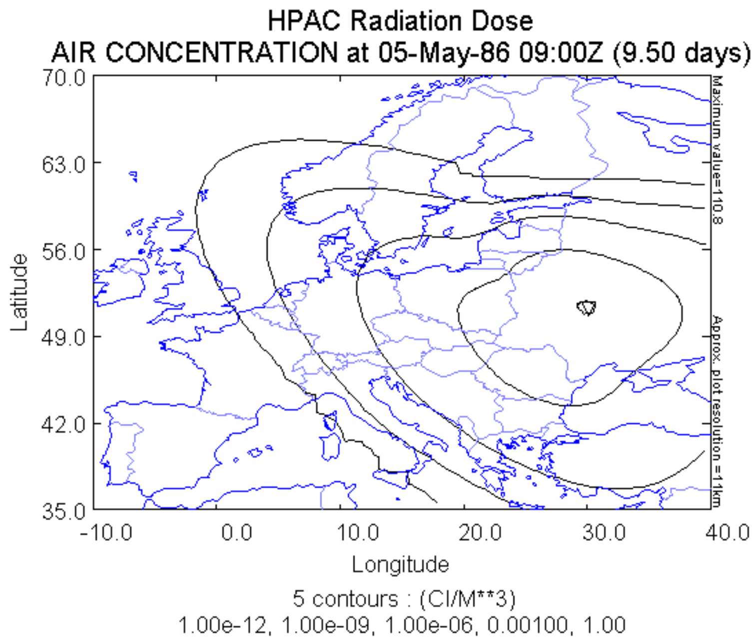

Figure 47. N-1B Hazard Plot of I-131 Air Concentration

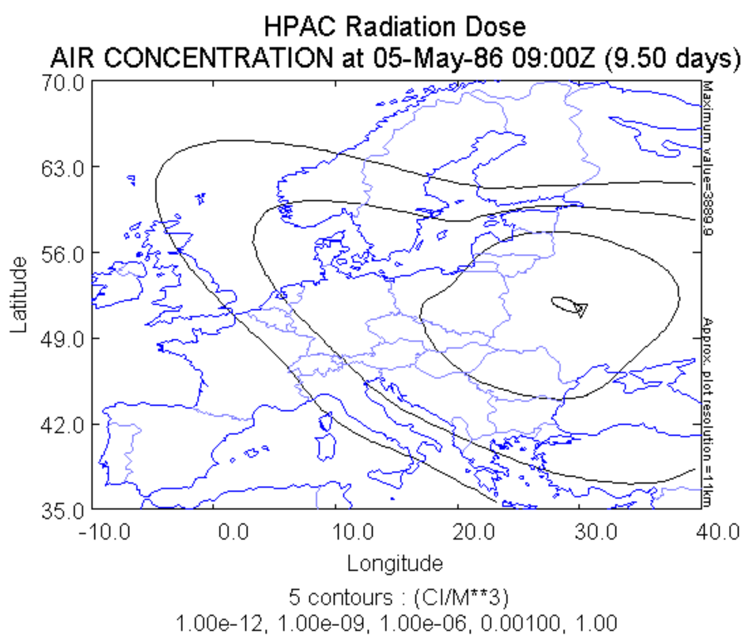

Figure 48. N-2 Hazard Plot of I-131 Air Concentration

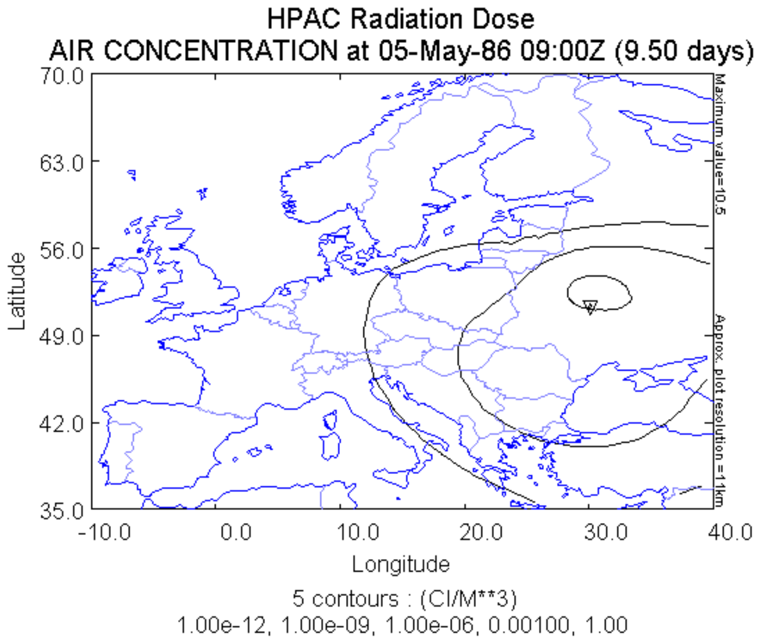

Figure 49. N-3 Hazard Plot of I-131 Air Concentration

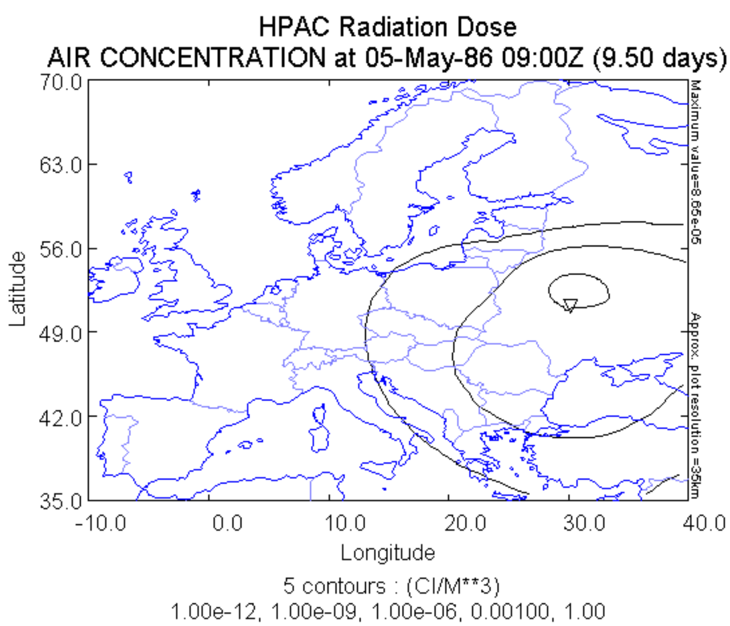

Figure 50. N-4 Hazard Plot of I-131 Air Concentration

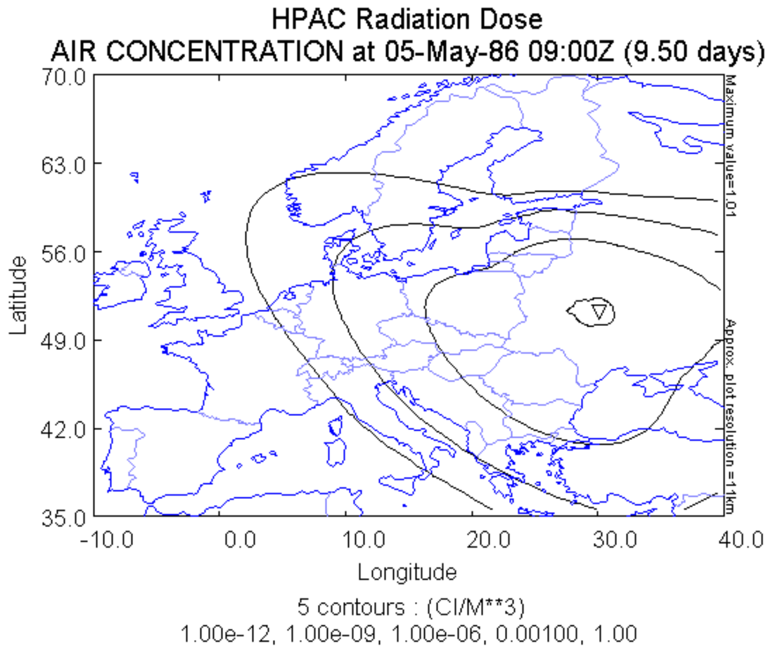

Figure 51. U-1 Hazard Plot of I-131 Air Concentration

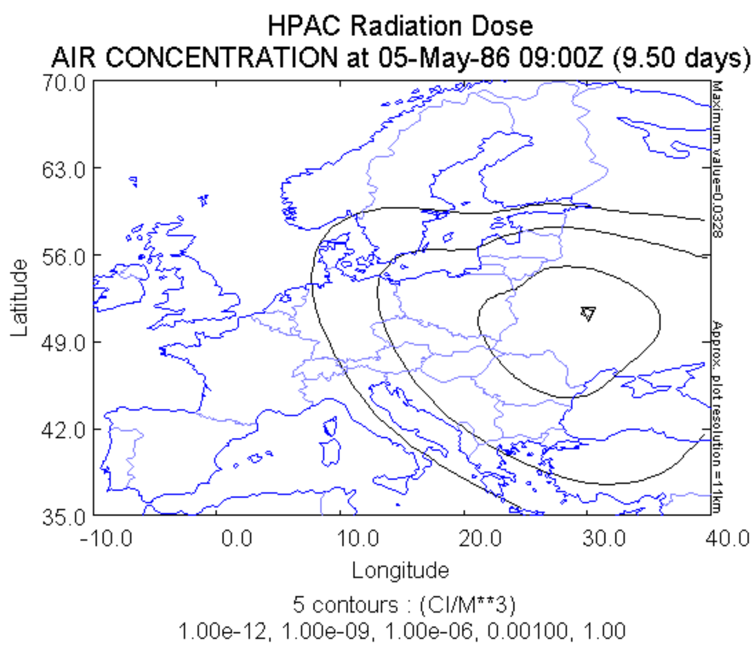

Figure 52. U-2A Hazard Plot of I-131 Air Concentration

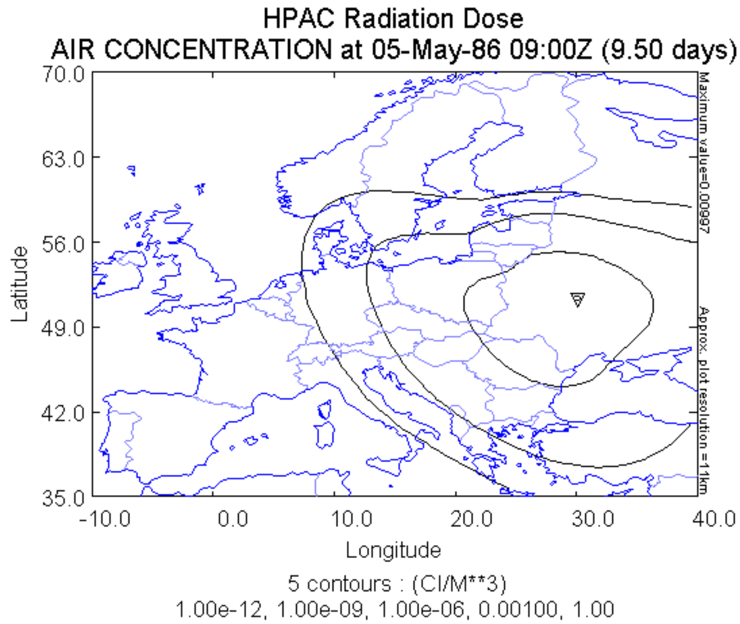

Figure 53. U-2B Hazard Plot of I-131 Air Concentration

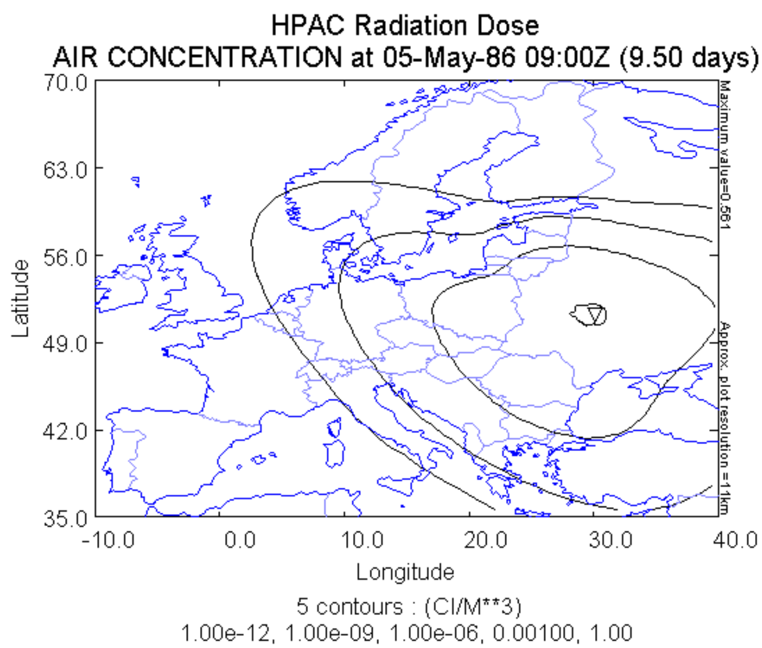

Figure 54. U-3 Hazard Plot of I-131 Air Concentration

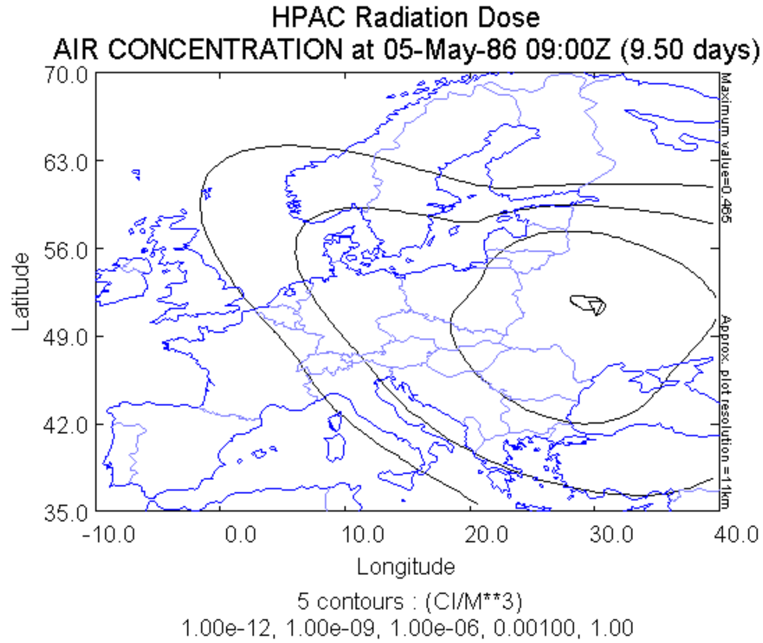

Figure 55. U-4A Hazard Plot of I-131 Air Concentration

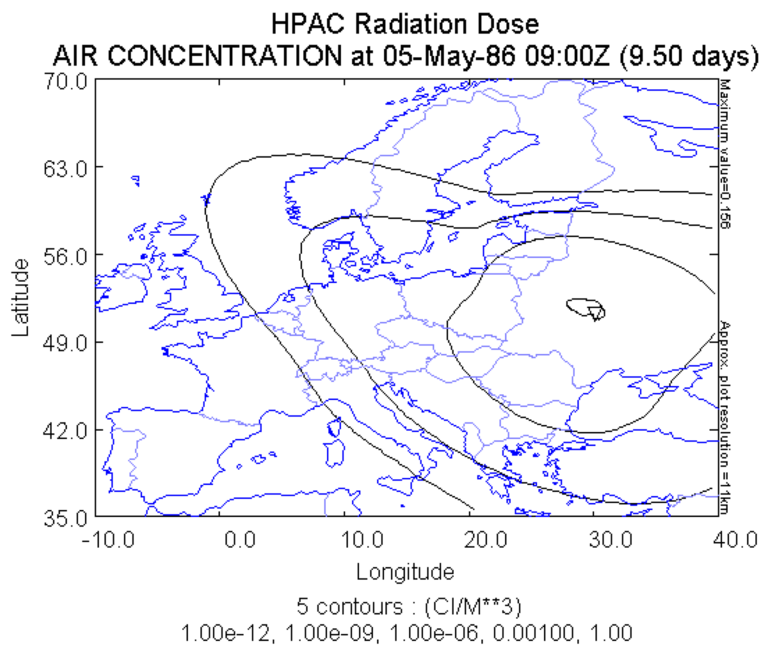

Figure 56. U-4B Hazard Plot of I-131 Air Concentration

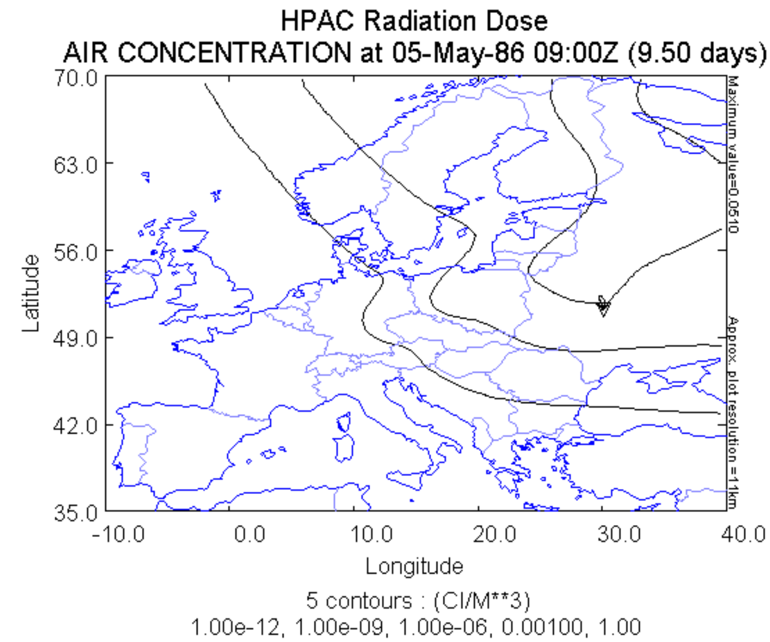

Figure 57. U-5 Hazard Plot of I-131 Air Concentration

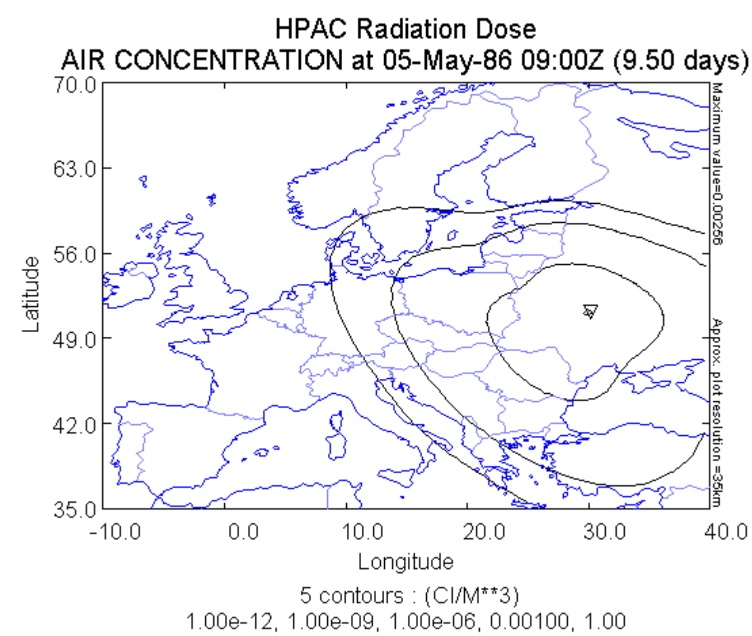

Figure 58. U-6 Hazard Plot of I-131 Air Concentration

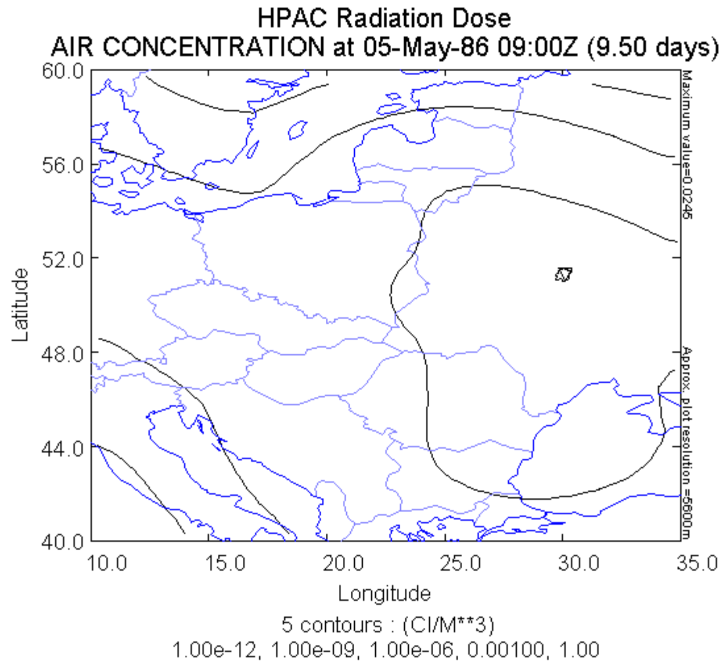

Figure 59. U-7 Hazard Plot of I-131 Air Concentration

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Vita

Major Dirk E. Plante was born [redacted]. In 1989, he earned a Bachelor of Science degree in Physics from Texas Christian University, Fort Worth, Texas. Major Plante received his commission into the United States Army Corps of Engineers in May 1989.

His first assignment after completing the Engineer Officer Basic and Ranger Courses was as a combat engineer platoon leader in Company A, 237th Engineer Battalion, Heilbronn, West Germany. After returning from Operations Desert Shield/Storm in May 1991, he became the executive officer for Company D, 237th Engineer Battalion. In June 1994 Major Plante completed the Engineer Officer Advanced Course, and was assigned to the 37th Engineer Battalion, Fort Bragg, North Carolina, where he commanded Company B and jumped out of perfectly fine Air Force aircraft dozens of times while in flight.

In September 1997 Major Plante was assigned to the National Imagery and Mapping Agency (NIMA) as an instructor at the Defense Mapping School (DMS), Fort Belvoir, Virginia, providing training to the Army's Military Occupational Specialty (MOS) 81T (Topographic Analysts) soldiers, and the Marine Corps' 0215D (Terrain Intelligence Specialists). In April 1999 Major Plante was assigned to the United States Forces, Korea (USFK), Assistant Chief of Staff, Engineer, in Seoul, South Korea as the command's Geospatial Information and Services (GI&S) Officer.

In August 2000 he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation he will be assigned to the Defense Threat Reduction Agency (DTRA) in Alexandria, Virginia.

REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
04-03-2002	Master's Thesis	Aug 2001 - Mar 2002

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
AN EVALUATION OF THE HAZARD PREDICTION AND ASSESSMENT CAPABILITY (HPAC) SOFTWARE'S ABILITY TO MODEL THE CHORNOBYL ACCIDENT	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Dirk E. Plante, Major, USA	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Building 640 WPAFB OH 45433-7765	AFIT/GNE/ENP/02M-06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The performance of the Nuclear Facility (NFAC) incident module in modeling a nuclear reactor accident is evaluated. Fallout predictions are compared with air concentration measurements of I-131 in Europe over a five-day period. Two categories of source term specifications are used: NFAC-generated source terms based on plant conditions and accident severity, and user-defined source terms based on specifying the release of I-131. The Atmospheric Transport Model Evaluation Study report source term provided the needed detailed release information. The Air Force Combat Climatology Center provided weather data covering Europe during the release's 11-day duration. For the NFAC-generated source terms as few as 20% and as many as 52% of the values are within the intended accuracy, depending on which source term specification was selected. For the user-defined source terms, values ranged 35% to 56% being within the intended accuracy, again depending on which source term specification was used. Performance improved in all cases for monitoring sites closest to Chornobyl, with up to 87% of the values falling within the intended accuracy. This indicates there may be a limit for selecting the spatial domain, making HPAC more useful as a tool for smaller spatial domains, rather than on a continental scale.

15. SUBJECT TERMS

Chernobyl, Chornobyl, Hazard Prediction and Assessment Capability, Second Order Closure Integrated Puff, Soure Term, Transport and Dispersion Model

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	125	LtCol Vincent J. Jodoin, ENP
					19b. TELEPHONE NUMBER *(Include area code)* (937) 255-3636 ext 4506